IC 9001

Bureau of Mines Information Circular/1985

Laboratory Wear Testing Capabilities of the Bureau of Mines

By R. Blickensderfer, J. H. Tylczak, and B. W. Madsen

UNITED STATES DEPARTMENT OF THE INTERIOR

Information Circular 9001

Laboratory Wear Testing Capabilities of the Bureau of Mines

By R. Blickensderfer, J. H. Tylczak, and B. W. Madsen

UNITED STATES DEPARTMENT OF THE INTERIOR
William P. Clark, Secretary

BUREAU OF MINES
Robert C. Horton, Director

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	L/min	liter per minute
cm	centimeter	m	meter
cm^2	square centimeter	mg	milligram
c/min	cycle per minute	min	minute
deg	degree	mm	millimeter
g	gram	mm^3	cubic millimeter
g/min	gram per minute	m/min	meter per minute
HB	Brinell hardness	mm^3/m	cubic millimeter per meter
h	hour	µm	micrometer
HRC	Rockwell C hardness	m/s	meter per second
in	inch	N	newton
J	joule	pct	percent
kg	kilogram	psi	pound per square inch
kPa	kilopascal	rpm	revolution per minute
kW	kilowatt	s	second
L	liter	wt pct	weight percent

Library of Congress Cataloging in Publication Data:

Blickensderfer, Robert
Laboratory wear testing capabilities of the Bureau of Mines.

(Information circular ; 9001)
Bibliography: p. 34-36.
Supt. of Docs. no.: I 28.27:9001.

I. Mechanical wear—Testing. I. Tylczak, J. H. (Joseph H.). II. Madsen, B. W. (Brent W.). III. Title. IV. Series: Information circular (United States. Bureau of Mines) ; 9001.

TN295.U4 [TA418.4] 622s [622'.028] 84-600209

CONTENTS

ILLUSTRATIONS

TABLES

LABORATORY WEAR TESTING CAPABILITIES OF THE BUREAU OF MINES

By R. Blickensderfer,[1] J. H. Tylczak,[1] and B. W. Madsen[1]

ABSTRACT

The laboratory wear testing capabilities of the Bureau of Mines are described. Wear tests are used to support the Bureau's research efforts toward reducing the wear of equipment used for mining and minerals processing and any wear involving a loss of strategic or critical materials. The emphasis is on abrasive wear because it accounts for most of the wear losses that occur in mining and minerals processing equipment. Spalling wear, caused by repetitive impact in grinding equipment, also is included. Ten abrasive wear tests, including high-stress and low-stress and two-body and three-body conditions, are described: dry-sand, rubber-wheel abrasive wear; Taber Abraser; abrasion resistance of refractory materials; dry-particle erosive wear; elevated-temperature, dry-particle erosive wear; low-angle slurry pot; jaw crusher gouging wear; ball mill wear; pin-on-drum abrasive wear; and high-speed impact gouging. Two repetitive impact tests are described: ball-on-block impact-spalling and ball-on-ball impact-spalling. Test equipment, procedures, and specimens are described, and typical test results are presented and discussed.

[1]Metallurgist, Albany Research Center, Bureau of Mines, Albany, OR.

INTRODUCTION

Wear is a major problem in the mining industry and occurs on a wide variety of items, such as excavator teeth, rock drill bits, crushers, slushers, ball mills and rod mills, chutes, slurry pumps, and cyclones. Wear results in a significant cost to the mining industry in terms of direct replacement costs, downtime, and maintenance. The Bureau of Mines is conducting research on various types of wear processes and materials. Wear mechanisms and the effects of variables such as alloy composition and heat treatment are being studied with the ultimate aim of devising alloy systems that reduce wear and significantly reduce the loss of critical and strategic metals. In order to support this research, a variety of laboratory test equipment has been purchased or constructed.

Although numerous types of wear tests have been reported, most are beset by lack of reproducibility or are too specialized to be of general interest. Only eight wear test practices have been published by the American Society for Testing and Materials (ASTM), although others are in process. The G.2 committee of ASTM, which is concerned with all types of wear, is devoting considerable effort toward developing wear test standard practices and procedures. The Bureau is working with the G.2 committee in this effort. The ASTM has published an evaluation of wear testing (1)[2] and, more recently, a volume describing a wide range of types of wear tests (2). Borik (3) compared several abrasion tests on a variety of abrasion-resistant materials.

An ideal laboratory wear test would be small in scale, produce highly reproducible data quickly, and simulate a wide range of field conditions. The test results should predict the wear of a material in actual service. Such a test is difficult to achieve because wear processes are dependent on a number of variables that are affected by time and scale. Some of these factors are frictional heating (lowering the flow stress), work hardening rate, size and nature of wear debris, nature of abrasive particles, microstructure of the material, and environmental interactions.

Consequently, hundreds of wear tests have been devised, each an attempt by an investigator to closely simulate a given wear situation while producing significant wear in a short time. There is a need to standardize and minimize the types of wear tests in order to make interlaboratory comparisons and to reduce the number of tests and types of test specimens required. At the same time, there is a need for the tests to more closely simulate a broader range of field conditions.

It is hoped that the following description of wear tests used by the Bureau will be helpful to other organizations involved in wear testing and wear research. The comparison of test parameters such as specimen size, duration of test, surface speed, etc. may be particularly useful to those attempting to select a suitable wear test. Also, this report may stimulate further ideas in wear testing and wear research that will eventually help reduce the tremendous losses in materials that result from equipment wear in mining and minerals processing in the United States as well as other countries.

DESCRIPTION OF TESTS AND EQUIPMENT

The Bureau of Mines has a total of 12 types of wear test units in use. Ten of these units are located at the Albany (OR) Research Center, where considerable research is being conducted on wear. The other two units are at the Rolla (MO) and Tuscaloosa (AL) Research Centers. Most of the Bureau's tests are related to

[2]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

abrasive wear, including erosive wear and slurry wear, because most wear problems in mining and minerals processing are caused by abrasive materials. Two tests involve impact-spalling wear--a major wear problem in crushing and grinding equipment. Other types of wear, such as adhesive wear and lubricated wear, are not being addressed. One study of wear between quartz and steel was conducted in 1976 at the Twin Cities (MN) Research Center (4), but the pin-wear test equipment that was used no longer exists. Similar pin-wear test equipment belonging to the University of Maryland was recently used at the Avondale (MD) Research Center for evaluating molybdenum diboride coatings.

Among the wear tests described, the dry-sand, rubber-wheel abrasion test is an ASTM standard practice (5) and the abrasion resistance of refractory materials is an ASTM standard test method (6). Two of the tests, the jaw crusher gouging abrasion test and the dry-particle erosion standard practice, were recently published by the ASTM. Of the remaining eight tests, three are novel tests devised by the Bureau, namely, the ball-on-ball impact-spalling test, the high-speed impact-gouging wear test, and the low-angle slurry pot test. The other five types of tests described are not ASTM standards but have been reported by other laboratories. In several cases, the Bureau has modified or improved the earlier tests.

Not included in this report are the frictional ignition tests at the Twin Cities, Albany, Avondale, and Pittsburgh (PA) Research Centers and the Los Angeles abrasion machine at Tuscaloosa Research Center. Although wear is inherent in the frictional ignition of methane-air mixtures, the frictional ignition equipment is not used at present to study wear processes or wear mechanisms although it may be so used in the future. The Los Angeles machine is for evaluating the abrasion resistance of aggregates, such as those used for concrete or asphalt paving. The tests, ASTM C131-81 and C565, are not pertinent to the thrust of the Bureau's research on wear of mining equipment.

ABRASIVE WEAR

Abrasive wear tests are frequently classified by the type of test equipment used; however, they can be classified in more general terms by the stress level and the geometrical arrangement of the components of the system (7, pp. 8-9). If the load is sufficient to fracture the abrasive particles, the wear is called high-stress abrasive wear; if the particles do not fracture significantly, it is called low-stress abrasive wear. The distinction between low-stress and high-stress conditions is not sharp. As for geometrical arrangement, if the abrasive particle is in contact with only one other object, it is called two-body abrasive wear. If the particle is engaged by more than one other object, such as another wear surface or other abrasive particles, it is called three-body wear. Although the abrasive material is normally harder than the wear object, this is not a necessary condition for classifying the wear as abrasive wear. Erosive wear is often categorized separately from abrasive wear. However, the erosive wear described in this report involves only solid particle erosion and therefore is considered as a type of abrasive wear.

Dry-Sand, Rubber-Wheel Abrasive Wear Test

The dry-sand, rubber-wheel (DSRW) abrasion test apparatus simulates low-stress, three-body abrasive wear. This type of wear occurs in the mining industry in linkages, pivot pins, and wire ropes, which suffer slow wear from the sliding and rolling action of abrasive fragments of rock and ore trapped between metal surfaces. Because this type of wear is slow, field trials alone would be too slow for evaluating new materials. The DSRW abrasion test is quick and gives a reasonable correlation with field tests. Even before the test became an ASTM standard (G65-81) in 1980 (5), it had been

used by a number of laboratories for many years. Since becoming an ASTM standard, it has become probably the most popular abrasive wear test in the United States.

The Society of Automotive Engineers (SAE) has developed but has not published a wet-sand abrasion test (8) that is similar to the ASTM dry-sand test. Some machines have been built to run both tests. SAE's wet-sand test has the advantage that the specimen does not heat as much as do the samples in a dry-sand test.

DSRW Equipment and Specimen

The basic ASTM machine consists of a rubber-rimmed steel wheel, 228.6 mm in diam by 12.7 mm wide, that turns at 200 rpm during a test; a sand hopper connected by a tube to a nozzle that allows a 250- to 350-g/min sand flow; a revolution counter that stops the drive motor after a set number of revolutions; and a weighted lever arm that holds the specimen and produces a horizontal force against the wheel where the sand is flowing. The sand is a 50- to 70-mesh silica test sand. The hardness of the rubber on the wheel must be durometer A-60±2.

The Bureau's machine includes a strain gauge and a tachometer, as shown in figure 1, although they are not part of the ASTM standard. The strain gauge supports the lever arm assembly at its pivot point, which is on a vertical line through the specimen-wheel interface. This allows measurement of the frictional force on the specimen during the wear test. The tachometer and a variable-speed drive make it possible to maintain a constant surface velocity on the rubber wheel as the diameter of the wheel decreases through either wear or surface dressing.

A typical test specimen is a rectangle, 25 by 76 mm, that is 3 to 13 mm thick. The wear surface is ground flat with a surface finish of at least 0.8 µm. The density of the test material must be known, to calculate the volume lost. The relatively simple shape of the test specimen is conducive to specimen preparation. Specimens of pure metals, steels, white cast irons, weld overlays, plastics, and ceramics have been made and tested.

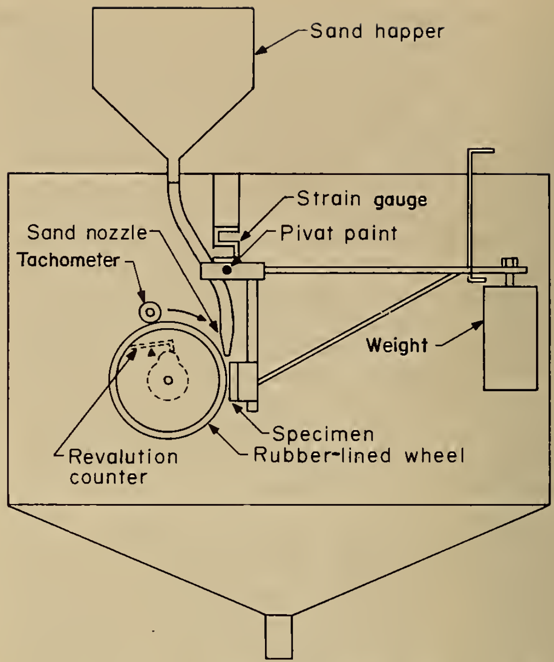

FIGURE 1. - Dry-sand, rubber-wheel abrasive wear test machine.

DSRW Procedure

The equipment has two test parameters: the sliding distance (number of wheel revolutions) and the specimen load. The ASTM recognizes four procedures using these parameters, as shown in table 1.

TABLE 1. - Standard conditions for the dry-sand, rubber-wheel abrasion test

ASTM procedure	Force on specimen, N	Wheel revolutions[1]	Distance abraded, m
A..........	130	6,000	4,309
B..........	130	2,000	1,436
C..........	130	100	71.8
D..........	45	6,000	4,309

[1]Based on a diameter of 228.6 mm. Must be increased with wheel wear.

A test consists of eight steps: (1) clean and weigh the specimen, (2) mount the specimen in the lever arm fixture and load the arm, (3) start the sand flow through the nozzle, (4) start the rubber-wheel drive motor, (5) release the lever arm so the specimen contacts the wheel and start the revolution counter, (6) stop the motor (automatic) and sand flow, (7) remove the specimen, and (8) clean and reweigh the specimen. From the weight loss and density of the material, the volume loss is calculated. The test is repeated one or more times. The coefficient of variation on a material must not exceed 7 pct to meet ASTM specifications.

DSRW Results and Discussion

Most of the Bureau's testing has been with a 130-N load on the specimen and 2,000 revolutions of the rubber wheel (ASTM procedure B). Typical volume losses have ranged from 5 mm^3 for sintered Al_2O_3 to 188 mm^3 for pure iron, with losses for most steels ranging from 30 to 120 mm^3. The reproducibility of the test is best for volume losses in the range of 20 to 100 mm^3.

In tests in which less than 20 mm^3 is lost, any small material inhomogeneities are exaggerated; therefore, a more severe test should be run by using either a greater sliding distance or more load. Above a 100-mm^3 loss, the groove becomes so deep that it may contact the edge of the rubber wheel and cause erratic results. Therefore, a less severe procedure may be desired. Using another procedure has a disadvantage in that test results cannot be directly compared among different procedures.

The DSRW test should be used only for ranking of various materials, not for absolute values of wear. For example, a material that wears half as much as another in the test probably will not last twice as long in the field because the test tends to exaggerate differences. Field factors such as the hardness and particle size of the abrading material will affect the absolute values of wear more than they affect the ranking. Typical wear data are presented in table 2.

Taber Abraser Test

The Taber Abraser[3] is a commercial wear tester designed to test the abrasive wear resistance of flat specimens of a wide variety of materials including coatings, paints, metals, plastics, paper, textiles, ceramic tile, and etched or printed material on glass. The wear condition can be classified as low-stress, two-body abrasive wear. The model 505 Taber Abraser, located at the Rolla Research Center, can test two specimens simultaneously, a feature useful for rapidly obtaining duplicate tests or for comparing two materials.

Taber Abraser Equipment and Specimens

Wear occurs by the action of a pair of abrasive wheels in contact with the specimen. The specimen is rotated at 72 rpm

[3]Reference to specific equipment is made for identification only and does not imply endorsement by the Bureau of Mines.

TABLE 2. - Typical dry-sand, rubber-wheel abrasive wear data

Alloy	Hardness, HB	Volume loss, mm^3	
		Procedure A	Procedure B
Stainless steel, type 304..	156	408	160
Mild steel, AISI 1020......	127	ND	133
Low-alloy steel, ASTM A514.	269	ND	122
Austenitic 12Mn steel......	197	ND	57.1
Low-alloy steel, AISI 5160.	280	ND	51.3
Cr white cast iron.........	710	31.5	12.7

ND Not done.

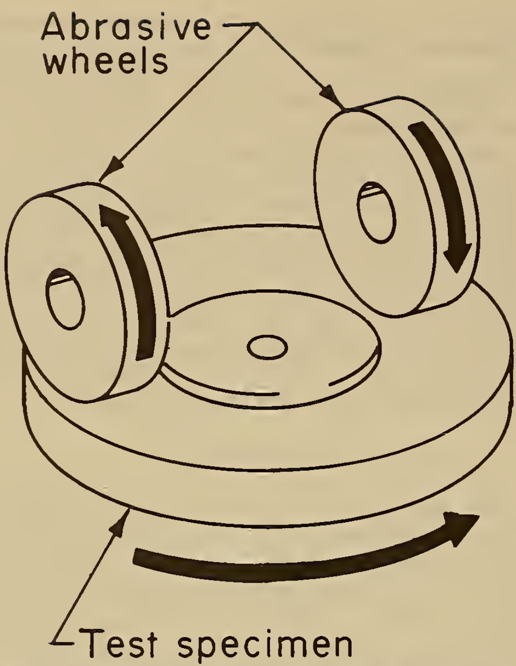

FIGURE 2. - Taber Abraser test, schematic.

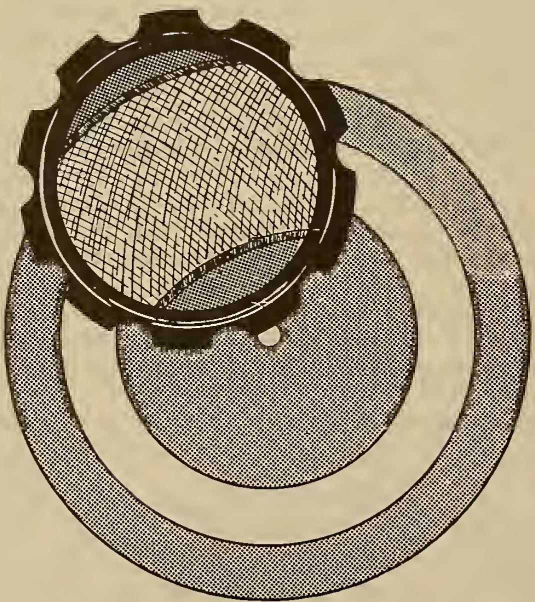

FIGURE 3. - Wear pattern produced by the Taber Abraser.

by a turntable, as shown in figure 2, which causes the abrasive wheels to drag and rotate. The horizontal axis of each abrading wheel is displaced from the vertical axis of the test material to produce the abrading motion between wheels and specimen. The abrasive action results in an "X" wear pattern over a ringed area of the specimen (fig. 3).

Test specimens range from 10 cm square to 16 cm in diam, depending upon the specimen holder. A hole of 6.4 or 9.5 mm is required in the center of most specimens. An area of 30 cm^2 is exposed to abrasion. The abrading wheels used for a test are selected to provide the desired abrasive quality. Five types of standard abrading wheels and other special wheels are available from the manufacturer. The wheels may contain silicon carbide or alumina abrasives over a range of particle sizes and may be bonded with either rubber or resin.

Taber Abraser Procedure

A test is conducted by placing the desired specimen on the turntable. The desired weight load is placed on the arms carrying the abrasive wheels. Loads of 125, 250, 500, or 1,000 g may be selected. The test is run continuously for a prescribed number of revolutions of the specimen: 10, 100, 1,000, or whatever the desired number. The count is displayed, and the unit will automatically stop at the prescribed count. A vacuum pickup collects abraded particles.

The test results may be evaluated by four methods, according to the manufacturer:

1. Visual endpoint method. Certain materials are best evaluated by observing the point at which they undergo a marked change in appearance or break down physically. By this method, the number of test cycles recorded on the counter is a wear index (rate of wear) of the sample. Materials that lend themselves best to this method are plated, glazed, or

polished surfaces; paper; textiles; and fabrics.

2. Weight-loss method. The weight-loss method of evaluation can be used when test results are compared with those of similar materials with about the same density. In this case, the Taber wear index is the loss of weight in milligrams per thousand cycles of abrasion for a test performed under a specific set of conditions.

3. Volume-loss method. When comparing the wear loss of materials of different density, it is usual to use the volume loss. The weight loss is converted to volume loss by dividing by the density of the material.

4. Depth-of-wear method. It may be desirable after abrasion tests to measure the depth of wear. This can be done with an optical micrometer calibrated in increments of one ten-thousandths of an inch.

Because of the wide variety of materials tested, types of abrasive wheels, loads, and revolutions, typical results cannot be reported. For a mild steel using a load of 1,000 g for 1,000 revolutions, the weight loss is about 30 to 60 mg, depending upon the type of abrasive wheel used.

Abrasion Resistance Test of Refractory Materials

The Bureau's abrasion resistance test equipment for refractory materials is located at the Tuscaloosa Research Center. The equipment and test procedure are described in ASTM designation C704-76a, entitled "Standard Method of Test for Abrasion Resistance of Refractory Materials at Room Temperature" (6). The method covers the determination of the resistance of refractory brick to a sandblast stream. The test measures the volume of material abraded from a flat surface at a right angle to a nozzle through which 1,000 g of size-graded silicon carbide grain is blasted by air at 448 kPa (65 psi). The test condition is classified as low-stress, two-body abrasive wear. The condition is considered low-stress because silicon carbide is tougher and more wear-resistant than the refractory brick normally tested.

A schematic of the test equipment is shown in figure 4. A sandblast gun fitted with a glass nozzle directs the abrasive toward the brick test specimen, which is enclosed in a dust-tight chamber. A bag on the vent from the chamber collects the dust. The precision of the test was found by round-robin testing to be ±15 pct.

Dry-Particle Erosive Wear Test

Dry-particle erosive wear can be classified as low-stress, two-body wear, the same type as in the preceding test. It simulates the wear conditions that occur in pipes, cyclones, and other equipment that carry fly ash or other particulate matter in a gas stream. A standard practice for conducting a dry-particle erosive wear test has been developed by the ASTM G.2 committee on erosion and wear. This practice may be used in the laboratory to measure the solid-particle erosion of different materials and has been used for ranking solid-particle erosion values of materials in simulated service environments (9-11). Actual erosion conditions involve particle sizes, velocities, and environments that vary over a wide range (9) in equipment such as cyclones, dust collectors, etc. Although one laboratory test cannot simulate the many conditions under which erosion may take place, data obtained over a range of particle velocities and impingement angles can help in the selection of wear-resistant materials.

Dry-Particle Equipment and Specimen

The essential components of the apparatus are shown in figure 5. The specimen is mounted in a chamber on a tiltable table to provide a range of impingement angles. The specimen chamber is shown in figure 6. An abrasive material (normally

50-μm, angular Al_2O_3) is carried by argon (or some other gas) through flexible tubing. The gas-solid mixture exits the hose through a nozzle that consists of a tungsten carbide tube, 1.5 mm in ID by 50 mm long. The abrasive particles and

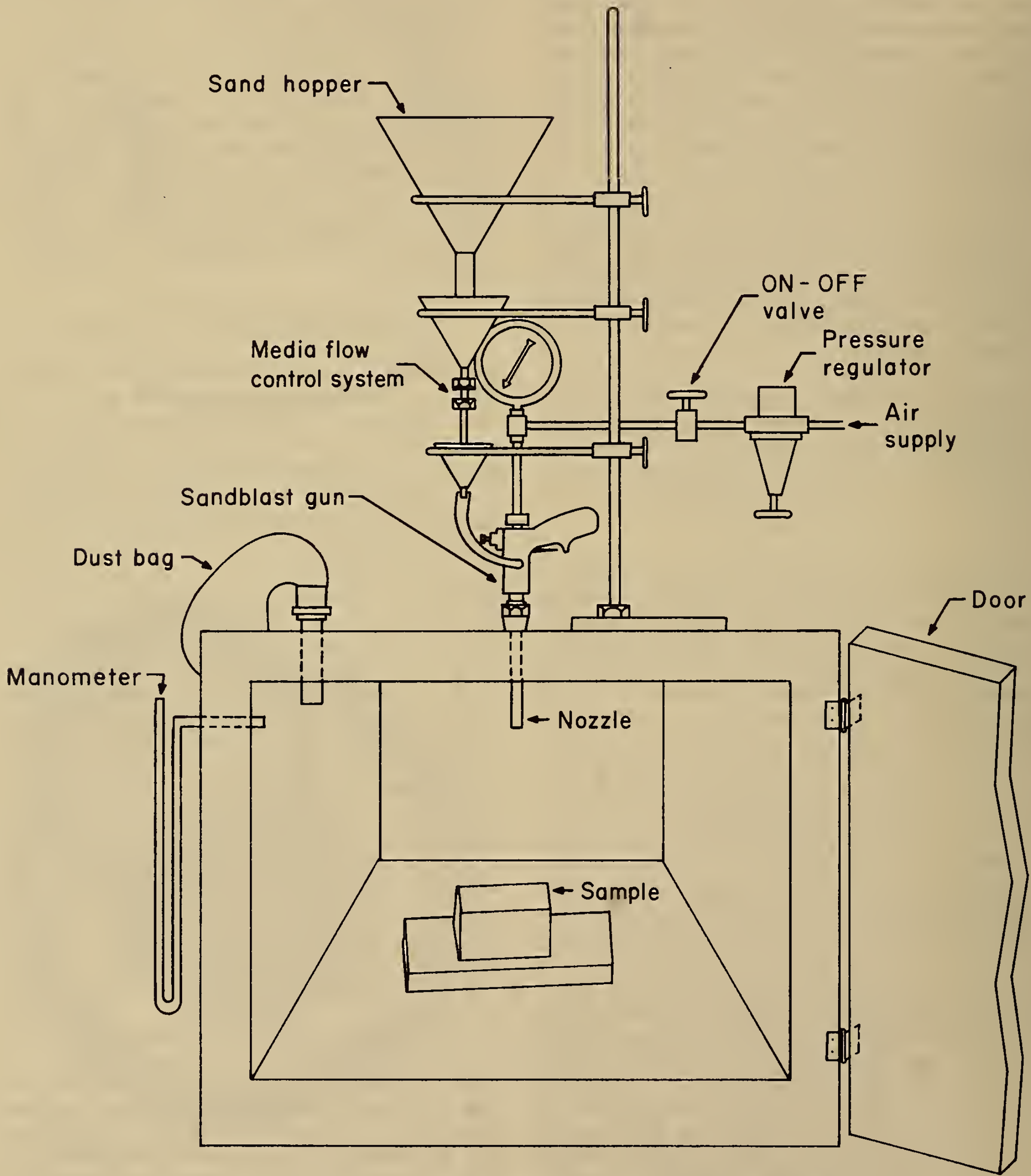

FIGURE 4. - Abrasion resistance test of refractory materials, schematic.

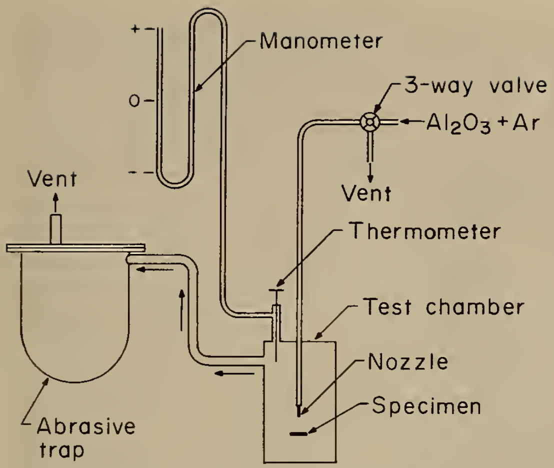

FIGURE 5. - Dry-particle erosive wear test apparatus, schematic.

gas are mixed and fed by an S. S. White model H Airbrasive unit. Mixing is accomplished within the Airbrasive unit by feeding particles from a pressurized container to a mixing chamber mounted on a vibrator. An orifice in the container bottom controls the flow of particles into the gas stream. The particle flux is a function of the voltage applied to the vibrator, and the velocity is a function of the gas stream pressure. The particle velocity is calibrated by a rotating double-disk device described by Ruff and Ives (12), and particle flux is calculated from the weight of abrasive collected in a given time.

A novel feature of the Bureau's apparatus is its ability to collect the abrasive used during a test run. Other investigators' apparatuses rely on preweighing the abrasive or collecting the abrasive during a blank run. In the Bureau's apparatus, the abrasive passes from the specimen chamber to a filter where it is collected. A manometer and a thermometer are used to measure the pressure and temperature of the specimen chamber.

Dry-Particle Procedure

Particle velocity and flow are measured and adjusted to proper conditions before specimens are tested. The specimens are polished through 400-grit abrasive, cleaned, and weighed to the nearest 0.1 mg. After a specimen is mounted in the proper location and orientation in the apparatus, it is subjected to particle impingement for 10 min. The specimen is then removed, cleaned, and reweighed, and the weight loss is calculated. The specimen volume loss is calculated by dividing the weight loss by the density of the specimen. The filter and specimen chamber are weighed before and after each run to determine the weight of abrasive used.

Dry-Particle Typical Results

Table 3 lists some typical test results for the erosive wear of 1020 steel, 304 stainless steel, and white cast iron.

TABLE 3. - Typical dry-particle erosive wear data: erosion loss, 10^{-3} mm^3 per gram abrasive

Impingement angle, deg	Mild steel, AISI 1020	Stainless steel, type 304	High Cr-Mo white cast iron
30 m/s:			
15.......	16.6	15.1	7.2
30.......	9.04	12.3	15.1
45.......	5.6	10.9	12.8
60.......	4.3	9.1	12.0
75.......	3.3	7.8	9.4
90.......	3.14	4.66	5.1

Impingement angle, deg	Mild steel, AISI 1020	Stainless steel, type 304	High Cr-Mo white cast iron
70 m/s:			
15.......	68.0	62.3	48.8
90.......	30.8	31.8	43.8
103 m/s:			
15.......	112.9	101.9	100.3
90.......	58.7	55.1	89.5

NOTE.--50-μm-diam Al_2O_3 particles carried by argon, 1.5-mm-diam nozzle.

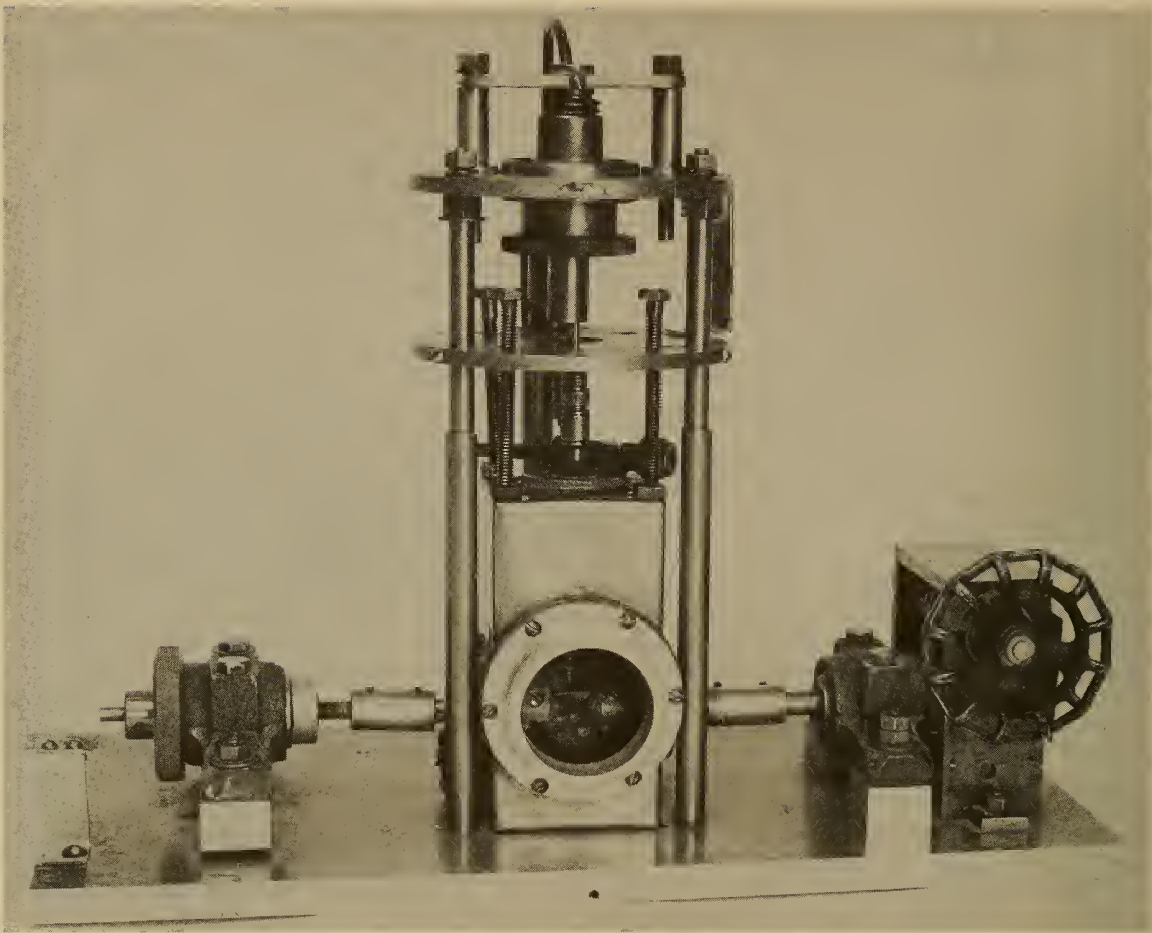

FIGURE 6. - Dry-particle erosive wear test, specimen chamber.

The data are expressed as the average volume loss of specimen per gram of abrasive. The table shows the effect of particle velocity and impingement angle on the wear of the specimens. At all three velocities, the high Cr-Mo white cast iron erodes less than the mild steel and stainless steel at a 15° impingement angle but erodes more than the mild steel and stainless steel at 90° impingement.

Elevated-Temperature, Dry-Particle Erosive Wear Test

Many industrial materials are subject to high-velocity abrasive particles at elevated temperature. Wear of this type is found, for example, in hot dust collection equipment. In order to select and develop materials for high-temperature use and to study the basic mechanisms of hot erosion, a laboratory test is necessary. Much has been learned about erosion at ambient temperature (10-13), but elevated-temperature work has been very limited. An apparatus suitable for studying hot erosion was designed and constructed by the Bureau. The test conditions are similar to those of the dry-particle erosive wear test, just discussed, except that the temperature can be elevated and the atmosphere can be controlled.

Three elevated-temperature erosion test devices have been reported. Doyle and

Levy (14) described a device capable of testing specimens from room temperature to 1,000° C with particle velocities ranging from 30 to 180 m/s. The angle of impingement could be varied. The specimen was heated in a small furnace, and the gas particle mixture was preheated. Young and Ruff (15) described a similar device, except the specimen was heated by passing an electrical current through it. Hansen (16) described the Bureau's apparatus in greater detail.

Elevated-Temperature Erosive Equipment and Specimens

The elevated-temperature erosion tester devised by the Bureau is shown schematically in figure 7. The apparatus consists of a vessel that contains a multiple-specimen holder on a turret, an electrical resistance heating element, a particle delivery nozzle, a shutter to conrol the abrasive blast duration, thermocouples, and an infrared pyrometer to monitor the temperature of the specimen surface within 10° C. The abrasive particles, typically 27-µm Al_2O_3, are delivered by an Airbrasive unit, as described in the preceding section. The particle delivery nozzle consists of a molybdenum shank about 4 cm long and a 1.3-cm sapphire tip, 0.058 cm in ID. The multiple-specimen holder accommodates 12 specimens, any one of which can be positioned beneath the nozzle during a run. The angle of incidence of the particles striking the specimen can be set by placing a wedge under the specimen. A vent in the vessel allows the driving gas to escape. Test specimens are approximately 1.5 by 1.5 by 0.2 cm. The test surface is ground through 400-grit abrasive.

Elevated-Temperature Erosive Procedure

Specimens are cleaned, dried, and weighed before testing. After 12 specimens are placed on the turret, the test chamber is sealed, heated in a partial vacuum, and filled with the desired gas, typically nitrogen. About 30 min is required to attain a temperature of 700° C. With the shutter closed between the nozzle and the specimen, the particle blast is started. After steady-state conditions are reached, the shutter is opened and the first sample is eroded for the desired time, typically 3 min. The remaining 11 specimens are eroded in the same manner. The furnace is then cooled by a stream of nitrogen gas and the specimens are removed, cleaned, and reweighed.

Three standard specimens made of Haynes Stellite wrought alloy 6B are run with the nine test specimens in each test. The volume loss of each specimen is calculated from its weight loss and density. The data are reported as the ratio of volume loss to the average volume loss for the three Stellite standard specimens. This ratio is referred to as the relative erosion factor (REF).

Elevated-Temperature Erosive Results

Table 4 contains erosion data for several materials tested at 700° C using

TABLE 4. - Hot erosive wear of several materials

Material	Nominal composition, wt pct	Relative erosion factor
MgAl oxide	$97MgAl_2O_4$-3MgO	2.76
Co-based hardfacing	Co-31Cr-12.5W-2.4C	1.61
Do	Co-30Cr-4.5W-1.5Mo-1.2C	1.00
Stainless steel, type 304	Fe-17Cr-9Ni-2Mn-1Si	.73
Stainless steel, type 316	Fe-17Cr-12Ni-2Mn-1Si-2.5Mo	.56
SiC, hot pressed	NAp	.44
B_4C, hot pressed	NAp	.21
Si_3N_4, hot pressed	NAp	.12

NAp Not applicable.

NOTE.--700° C, 90° impingement, 27-µm Al_2O_3 particles, 5-g/min particle flow, 170-m/s particle velocity, 3-min test duration, N_2 atmosphere.

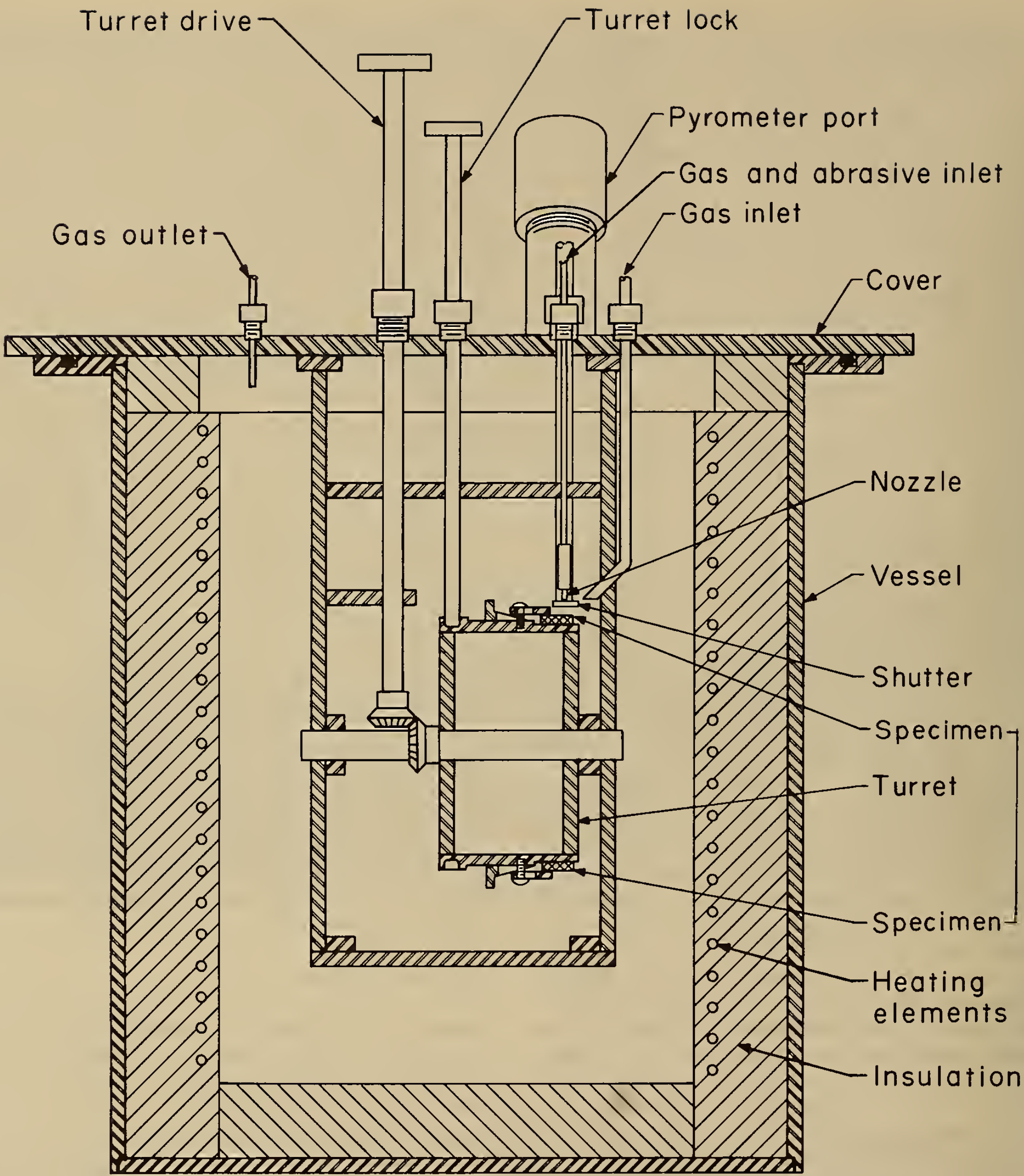

FIGURE 7. - Elevated-temperature erosion tester, schematic.

nitrogen gas and 27-µm Al_2O_3 particles at 90° impingement. The data reflect the average values for a set of five tests. One standard deviation of a set of tests was typically within 10 pct of the mean. The data reported include a wide range of REF values.

Low-Angle Slurry Pot Test

Transporting minerals as a slurry is an efficient means of transportation and is done during many mineral beneficiation processes. However, the movement of slurries can cause significant wear to

the slurry-handling equipment, especially in places where the flow changes direction. Wear caused by slurries is an economic concern of industry. Pumps, elbows, tee junctions, and hydrocyclones are component parts of slurry transport systems that are exposed to severe wear. In a slurry, abrasive erosion is produced by the solid particles, and corrosion may be produced by the liquid; the two are frequently synergistic. Reliable experimental wear data are needed to aid in the design of slurry transport equipment.

Types of slurry wear tests reported in the literature include slurry pot, pipeline, and jet impingement. All of these involve low-stress, two-body abrasive wear. Many variations of a slurry pot test have been devised. Jackson (17) used a rotating wire, Tsai (18) used two rotating metal tubes, and Bess (19) used a rotating disk as specimens in baffled pots containing abrasive slurries. These slurry pot tests relied on experimental reproducibility because only one type of specimen was used in any one test. In addition, the impingment velocity was based on the assumption that baffles in the pot held the slurry stationary. Postlethwaite (20), Hocke and Wilkinson (21), and Elkholy (22) used closed-loop slurry pipeline test systems. Postlethwaite used rectangular specimens that were flush with the inside wall of the pipeline, and Hocke used rectangular specimens with a slurry jet impingement tester. All of the above-mentioned slurry wear tests have the problems of abrasive particle degradation and slurry contamination by wear debris. These problems are inherent in tests that recirculate the slurry for prolonged times. The low-angle slurry pot test devised by the Bureau is normally operated in a flowthrough mode that essentially eliminates the problems of particle degradation and slurry contamination.

Slurry Pot Equipment and Specimens

The Bureau's slurry test apparatus is a slurry pot consisting of an impeller that rotates the slurry past an array of specimens located around the inside of the pot. Thus, the impingement angle is low or nearly tangential. A schematic of the equipment is shown in figure 8. The slurry pot consists of a plastic ring with 16 sides that form a hexadecagon to hold specimens. This central section is bolted to a stainless steel top and bottom and is sealed with O-rings. In order to avoid galvanic effects between unlike specimens, eight specimens are alternated with eight plastic inserts around the inside of the plastic ring. Both the specimens and plastic inserts are 24 by 32 mm and 10 mm thick. The plastic inserts are made of ultrahigh-molecular-weight polyethelene, which has proven very wear resistant. The ends of the specimens are beveled to fit adjacently inside the plastic ring. The test surface of the specimen is surface-ground and polished through 400-grit abrasive before each test.

The impeller is made from a commercial helical gear made of hardened steel that rotates to move the slurry past the stationary specimens. Dry sand is fed through a nozzle to a slurry hopper where the sand is mixed with the liquid. In tests conducted with this flowthrough system, typically, tapwater is fed to the system at a rate of 4.34 L/min and the sand is fed at 88 g/min, which results in a mean retention time for the sand in the slurry pot of only 2 s. The slurry discharges to a settling basin where the solids settle and the water flows to a drain. A modified drill press supports the slurry pot and drives the helical gear. A magnetic pickup provides a means to electronically measure the impeller tip speed, which can be varied from 1.3 to 22.4 m/s by changing the belt system in the drill press. The temperature of the slurry is monitored at the discharge of the slurry pot. The equipment is illustrated in figure 9.

Alternatively, the slurry can be recirculated by shifting the slurry discharge back into the slurry hopper, as shown in figure 8. This alternate mode can be used to study the changes in particle

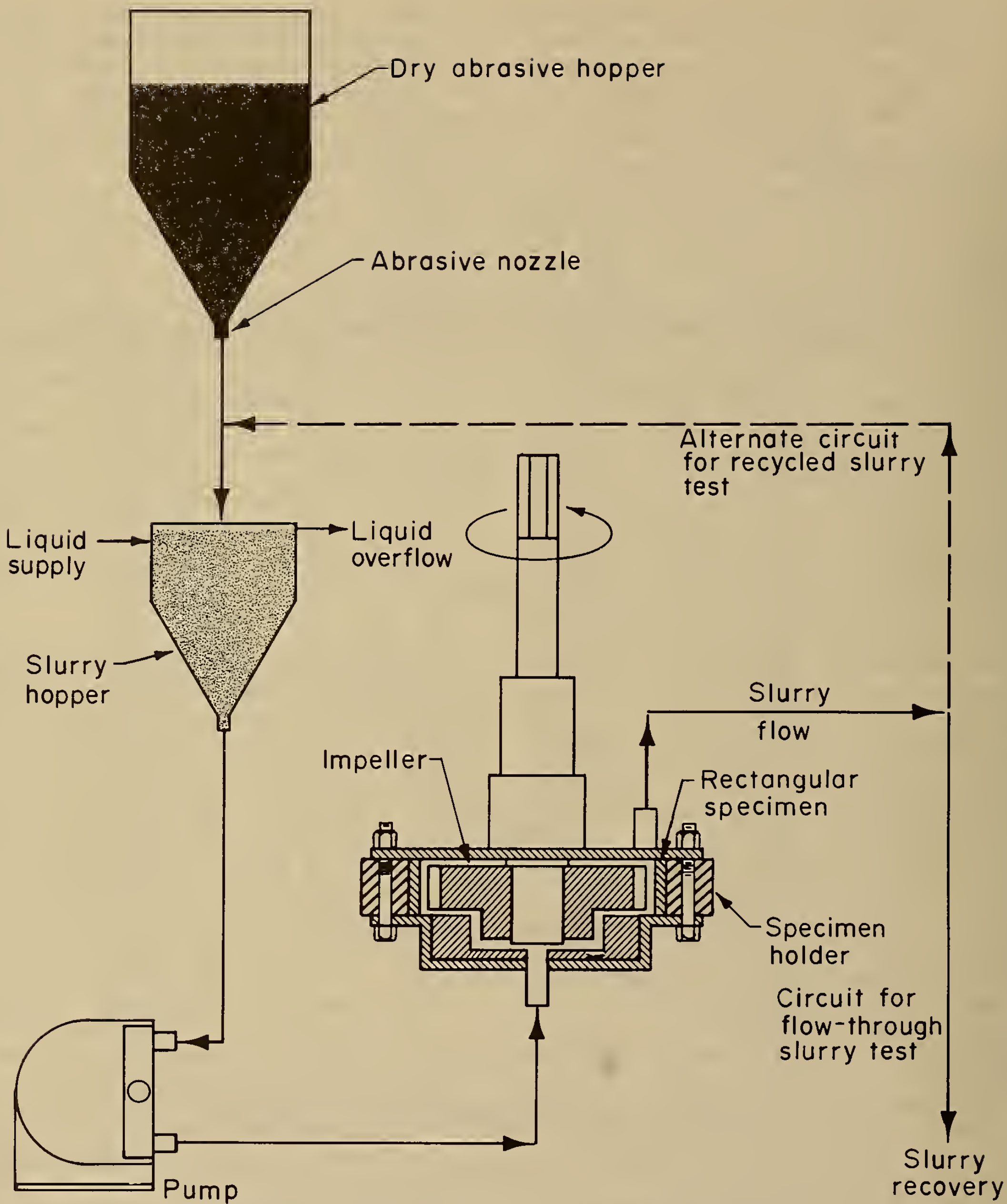

FIGURE 8. - Low-angle slurry pot equipment, schematic.

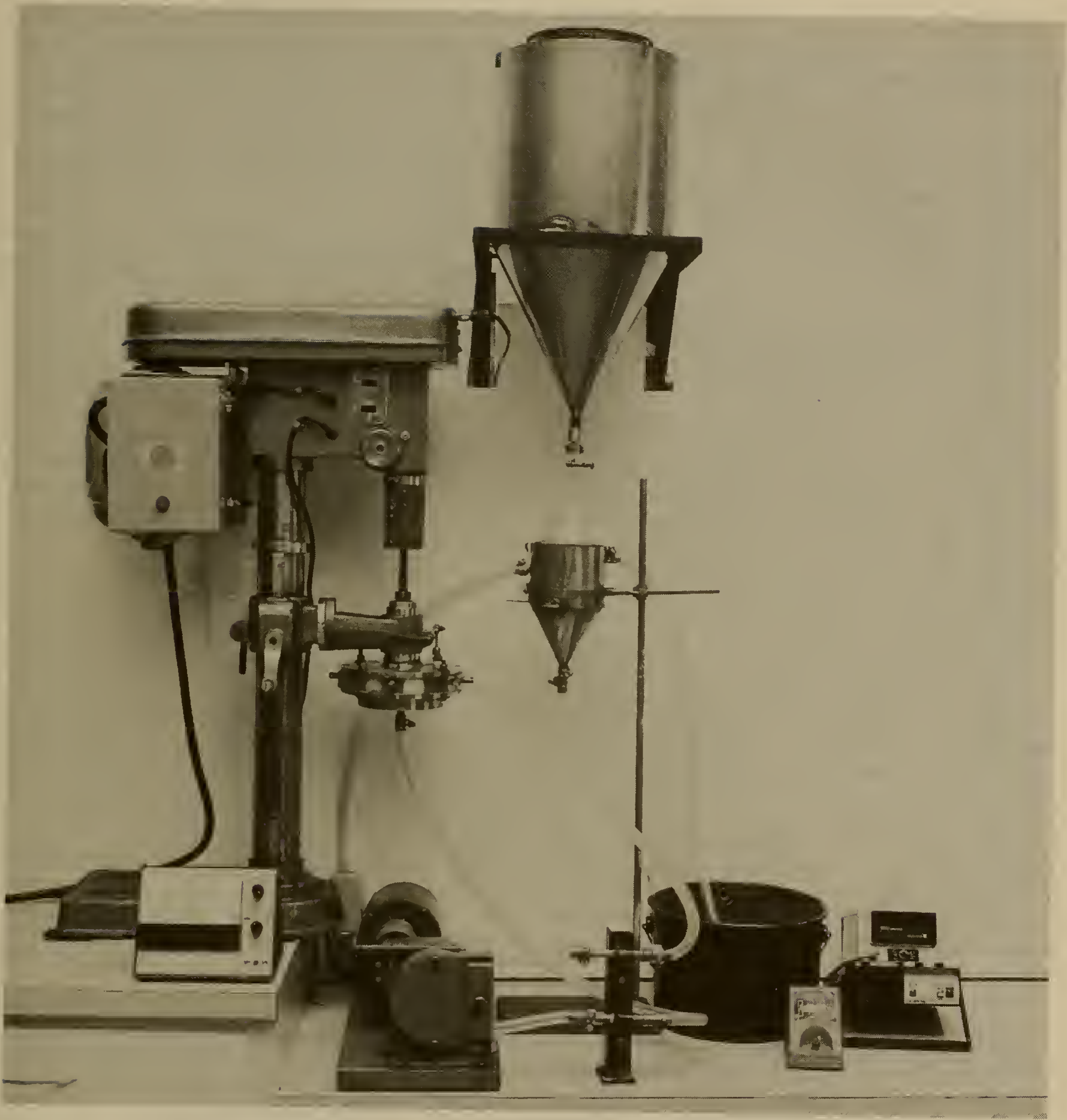

FIGURE 9. - Low-angle slurry pot test equipment.

shape and roughness and their effect on wear rates. Tests such as these also can be used to characterize wear mechanisms.

Slurry Pot Procedure

Specimens are prepared for testing by cleaning, drying, and weighing to the nearest 0.1 mg. Up to eight specimens along with the plastic inserts are placed inside the plastic center ring. Replaceable inserts above and below the specimens ensure that the specimens are electrically insulated from the stainless steel top and bottom sections.

The mass flow rates of the dry abrasive solids and the solution are each adjusted prior to the test to provide the desired percent solids and slurry flow rate. After the solution is pumped through the system for a few seconds, the helical gear and sand flow are started, and the time is noted. After a predetermined test time, the slurry pump and helical gear are stopped, and the samples are removed, cleaned, dried, and weighed. The specimens are put back into the slurry pot, and the test is repeated several times. The volume losses are calculated and recorded as a function of time. Curves of time versus volume loss are then compared with data obtained with standard AISI A514 steel specimens. The test procedure in the recirculating mode is essentially the same, except the percent solids is determined by the initial mass of solids and solution put into the system.

One of the attributes of the flowthrough system is that the temperature of the slurry is nearly constant and is determined by the temperature of the liquid supply. When recycled slurry is used, a means of heat exchange at the slurry hopper is required to prevent overheating of the system.

Specimens can be reused after regrinding and repolishing the wear surface and regrinding one beveled edge. Plastic inserts are placed behind the reground specimens in order to maintain the same clearance between the rotating gear and the specimen surface. This assures the same geometry inside the pot and gives a constant exposed area of wear surface. The size of the specimens allows two to be made from each previously worn specimen from dry-sand, rubber-wheel abrasive wear tests or jaw crusher tests.

Slurry Pot Results

Typical results of wear testing with the low-angle slurry pot are presented in table 5 for both flowthrough and recycled slurry tests. Results of the flowthrough tests showed that the wear rate is constant with respect to time. In contrast, conventional slurry tests that use a recycled slurry give decreasing wear rates with time (17-22). In addition, table 5 shows that lower wear rates were obtained with recycled silica sand. The lower wear rates result from the rounding of the slurry particles during the test. The ranking of specimens with

TABLE 5. - Typical low-angle slurry wear data for several metallic specimens: wear rate, cubic millimeter per hour

Specimen type	Flowthrough slurry	Recycled slurry		
		0.33 h	0.67 h	1 h
Stainless steel, type 304....	22.1	12.1	4.85	1.94
Low-alloy steel, ASTM A514...	21.1	6.10	2.54	1.06
Mild steel plus 2 pct Si.....	21.2	5.42	.274	.014
Low-alloy steel, AISI 4342...	6.99	1.60	.028	.001
Ni-based hardfacing..........	3.56	1.36	.778	.444
Co-based hardfacing..........	2.40	1.46	.163	.018

NOTE.--Water with 2-pct silica sand (minus 50 plus 70 mesh), 17° C, 15.7 m/s.

respect to wear rate also can change during a recycled slurry test. For example, after 1 h, the fifth specimen had a greater wear rate than the fourth specimen.

Jaw Crusher Gouging Abrasion Test

Gouging wear occurs in many mining operations, for example, where excavator teeth or loaders penetrate or drag over rock, and in jaw and gyratory crushers. Gouging wear is identified by the removal of a significant amount of material (a gouge) from the wear object after an encounter by the abrasive object in which the abrasive object also suffers damage. It is a type of high-stress wear that may be produced by either two-body or three-body conditions. The jaw crusher test gives high-stress, three-body abrasive wear. Jaw crusher wear tests were pioneered in the United States by Borik (23-24), improved by Fuller,[4] and used abroad by Sare and Hall (25). The jaws that crush the rock are taken as the test specimen. Several investigators believe that the jaw crusher test gives the closest correlation to wear that occurs on earth-penetrating equipment, such as excavator teeth, power shovel buckets, scoops, and grader blades, as well as real jaw crusher wear. ASTM committee G.2 has developed a new standard practice for the jaw crusher gouging abrasion test.

The Bureau's jaw crusher test equipment is considerably smaller than any reported in the literature. The smaller size gives greater economy of rock consumed and smaller specimen size. Typical values for the Bureau's test compared with typical values used in previous tests are--rock consumed, 91 kg versus 910 kg; specimen size, 1 by 2.5 by 7 cm versus 2 by 7 by 15 cm; and specimen weighing precision, ±1 mg versus ±100 mg.

[4]Fuller, W. (Esco Corp., Portland, OR). Private communication.

Jaw Crusher Equipment and Specimen

A small commercial laboratory jaw crusher was modified to accept an easily machined, identical pair of test wear plates and a similar pair of reference wear plates. One test plate and one reference plate are attached to the stationary jaw, and the other test and reference plates are attached to the movable jaw, such that a test plate and a reference plate oppose one another. A rock hopper and rock chute are attached above the jaw crusher. The arrangement of the jaw crusher test equipment is shown in figure 10, and a photograph is presented in figure 11. The jaw crusher operates at 260 c/min.

The jaw crusher was extensively rebuilt and strengthened in order to transform it from a crude laboratory crusher into a precision wear test apparatus. The jaw opening, originally 7.5 cm (3 in) wide, was reduced to 5 cm (2 in), thus providing a specimen width of 2.5 cm (1 in). An alloy steel eccentric shaft of larger diameter was made, heattreated, and fitted with needle bearings. New bearing blocks were made and welded to reinforced side plates. New jaws that would hold test specimens were made, and the jaw opening adjuster was redesigned and rebuilt. The original 1.1-kW drive motor was replaced with a 3.7-kW motor. Because of the many modifications, it is recommended that anyone wanting a jaw crusher test machine should design and construct a completely new unit instead of rebuilding an existing jaw crusher.

The test wear plates and reference wear plates have a 15° taper on each end for clamping to the jaws. All specimen surfaces are machined on a surface grinder. The small size of the specimens has a distinct advantage because previously used specimens from dry-sand, rubber-wheel abrasion tests can be used in the jaw crusher after regrinding. The standard reference material used is a

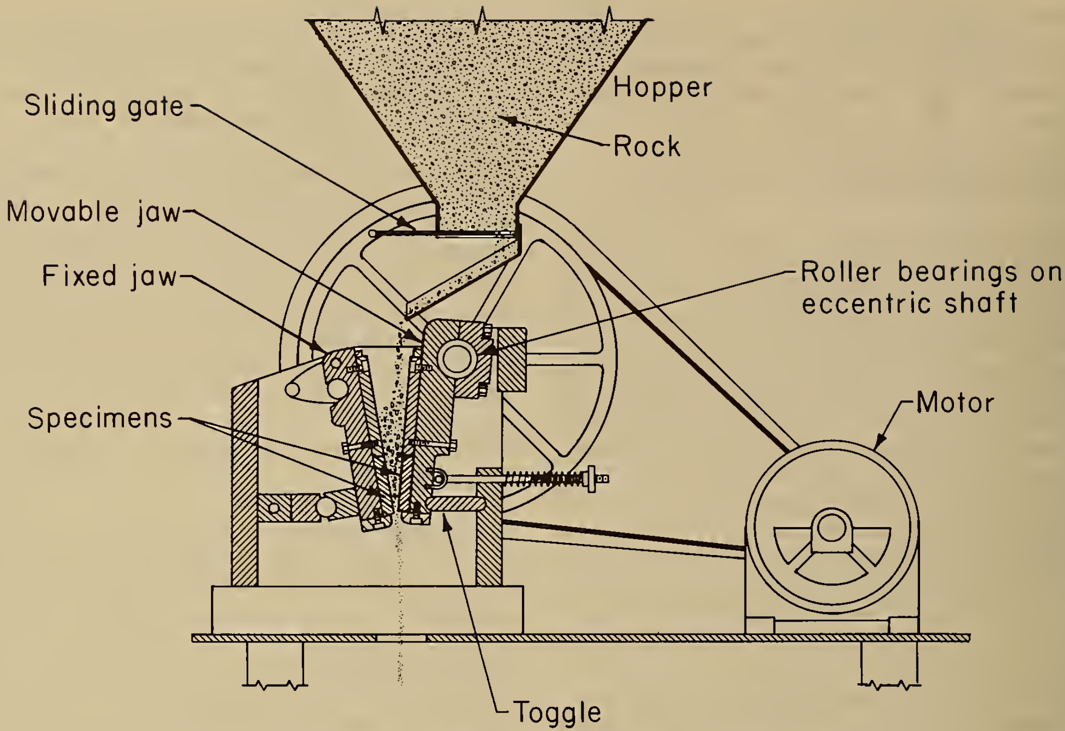

FIGURE 10. - Jaw crusher gouging wear test machine, schematic.

low-alloy steel, ASTM A514, with a Brinell hardness of HB 269.

The test gives wear of a test material relative to a standard steel. Because the test is relative, variables in the rock have little effect on test results. Therefore, the size distribution and mineral composition of the rock are not specified.

Jaw Crusher Procedure

After the four wear plates are cleaned and weighed to ±1 mg, they are clamped to the jaws with a standard plate opposing a test plate. The minimum jaw opening is set to 3.18 mm (0.125 in), and a 45-kg load of prescreened rock, minus 2 cm (3/4 in), is run through the crusher. The minimum opening is reset to 3.18 mm, and another 45 kg of rock is crushed. The specimens are recleaned by vigorous scrubbing with a bristle brush. The volume loss may be calculated from the mass loss, determined by weighing, and the known densities of the test materials. A wear ratio is developed by dividing the volume loss of the test plate by the volume loss of the reference plate. This is done separately for the stationary and movable plates. The two wear ratios are then averaged for a final test ratio. The smaller the figure for the wear ratio, the better the wear resistance of the test plate.

Jaw Crusher Typical Results

After crushing 90 kg of rock, the typical weight loss of the standard steel specimen was 0.4 g on the fixed jaw and 5 g on the movable jaw. The wear ratios of test specimen to standard steel are given for several materials in table 6. Tests on materials having greater abrasive wear resistance than the standard gave wear ratios less than 1. For example, hardened AISI 4340 steel gave a wear ratio of 0.157, and a high Cr-Mo white cast iron,

FIGURE 11. - Jaw crusher gouging wear test machine.

TABLE 6. - Typical jaw crusher gouging wear data

Alloy	Hardness, HB	Wear ratio
Low-alloy steel, ASTM A514....	269	1.000 ±0.030
Austenitic 12Mn steel.........	187	.284
Low-alloy steel, AISI 4340....	603	.157
6Ni-8Cr white cast iron.......	588	.134
High Cr-Mo white cast iron....	555	.0823

NOTE.--Minimum jaw opening set at 3.18 mm (0.125 in); standard jaw of A514 steel, HB 269; 90 kg (200 lb) of rock crushed.

known for its superior abrasive wear resistance, gave a wear ratio of 0.0823.

The precision of the jaw crusher is determined after every six test runs. This is done by making a run in which all four specimens are of the standard steel. The average wear ratio of the two pairs of specimens must be 1.000±0.030, according to ASTM recommendations on the jaw crusher test. The average ratio for the Bureau's tests fell within this limit.

Ball Mill Wear Test

When a lump of ore is crushed by the impact between two balls in a ball mill, it is considered high-stress, three-body abrasive wear. The abrasive wear of balls that results from the milling of ore is the major wear loss in most minerals processing plants. During the wet milling of ores, abrasive wear is combined with corrosion. Abrasion and corrosion are synergistic: a corroded surface is more easily abraded than an abraded surface and an abraded surface is more easily corroded than a corroded passivated surface. Thus, each enhances the other. Natarajan (26) showed that abrasive wear loss was much greater than corrosion loss on steel balls during the laboratory ball milling of magnetic taconite. Bond (27) reported that wear rates during grinding became extreme as the pH of the liquid dropped below 5.5. Ellis (28) did extensive tests on the effect of pH and atmosphere on steel balls while wet grinding sand in small 0.3- and 1-m-diam mills. Norman and Loeb (29) extended the work to include the grinding of molybdenum ore in 3-m-diam mills.

The Bureau set up an apparatus to study wear caused by erosion-corrosion of specific ores and liquids. Two sizes of mills are used, a small mill, 12 cm ID, and a larger mill, 60 cm ID. The smaller mill is more convenient for laboratory research, but the surface of the test specimens may passivate because the small impacts may not significantly abrade the protective layer. That is, synergism may not occur. The larger mill assures more aggressive abrasion that is closer to the conditions in commercial mills.

Ball Mill Equipment and Specimens

The small ball mill is a commercial 12-cm-diam porcelain mill with five silicone rubber lifters added inside. The drive rotates the mill at 120 rpm. Figure 12 shows the mill with typical specimens, rock, and liquid for a run.

The larger ball mill (fig. 13), is 60 cm in diam by 20 cm long. It was fabricated from steel and lined with natural rubber, 1 cm thick. The interior of the mill has 12 lifters, each 2 cm high. In operation, the mill is entirely closed except for a vent in the center to prevent buildup of gas pressure. One end of the mill can be unbolted and removed for loading specimens, rock, and liquid. The mill is rotated by two rollers driven by a 2.7-kW motor that drives the mill at 43 rpm or 75 pct of critical speed. A wooden cover fits over the mill and drive

FIGURE 12. - Small ball mill with specimens, liquid, and rock.

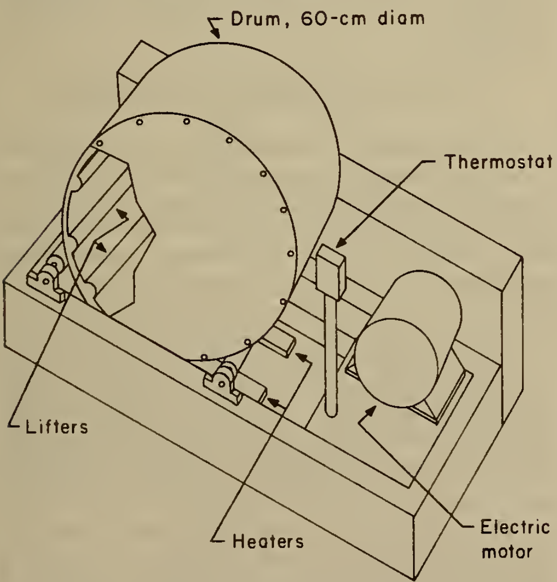

FIGURE 13. - Ball mill test equipment, schematic.

assembly. A heater and thermostat within maintain constant temperature during a run.

The specimens used in the small ball mill are oblate spheroids about 2 cm in diam by 1 cm thick. Specimens of a wide range of alloys are conveniently prepared in an inert atmosphere box by arc-melting the starting materials on a copper hearth plate. The surface finish of such specimens is relatively smooth and requires little or no further grinding before testing.

The test specimens used in the larger mill are cylinders, 5 cm in diam by 5 cm long, that are conveniently made by cutting commercial 5-cm rods into 5-cm lengths. Noncommercial alloys are made by casting in a sand mold. The cast specimens are sandblasted and rough ground.

Ball Mill Procedure

To conduct a test in either ball mill, specific amounts of liquid and ore or rock are selected to provide a slurry. The ratio of ore weight to total surface area of the specimens is kept the same in both mills for comparison of results. Typically, 1.13 L of liquid, 3.8 L of ore, and six specimens are used in the larger ball mill. Test specimens are cleaned, dried, and weighed. The ore is put into the mill and is warmed to the desired operating temperature, normally 35° C. The test specimens and liquid are added to the ore, and the temperature and pH are measured. The mill is then sealed and run at constant temperature. After 1 h of running time, the mill is opened, the temperature of the slurry is measured, and the specimens are removed and cleaned with water and a soft nylon brush. A sample of the slurry is filtered, and the pH is measured. The tests on a given material are repeated until a consistent trend in weight loss is obtained. The surface area of each specimen is determined, and from the density and mass loss during the test time, the erosion-corrosion rate in mils per year (1 mil = 0.001 in) is calculated.

Ball Mill Results and Discussion

A study of erosion-corrosion of grinding media during the grinding of Florida phosphate rock with recycled waste phosphoric acid showed some characteristics

of the two ball mills. This slurry was quite acidic, ranging from an initial pH of 2 to a final pH of 3 after the 1-h test. Erosion-corrosion wear data on four alloys are given in table 7. Corrosion-resistant materials, the nickel-base alloy, Hastelloy C-276, and the stainless steel, type 316, had good wear resistance in the small ball mill where impacts were small. In the large ball mill, however, the wear rate increased about 10 times. Apparently the larger mill produced impacts sufficient to remove the passivated film, thereby allowing an erosion-corrosion synergism. The data show that the large ball mill should give a more accurate correlation with industrial wet-grinding mills.

TABLE 7. - Ball mill erosion-corrosion of several materials, using phosphate rock and waste phosphoric acid, mils per year

Alloy	13-cm mill	60-cm mill
Ni-Cr white cast iron......	2,590	1,930
High-C steel, AISI 1090....	2,240	1,420
Stainless steel, type 316..	118	1,090
Ni alloy, Hastelloy C-276..	47	559

Pin-on-Drum Abrasive Wear Test

The pin-on-drum abrasive wear test involves high-stress, two-body abrasive wear. One end of a cylindrical pin specimen is moved over an abrasive paper, abrading material from the specimen and crushing the fixed abrasive grains. The wear is believed to simulate wear that occurs during crushing and grinding of ore--processes in which the abrasive particles are crushed, therefore called high-stress abrasive wear.

Considerable pin-abrasive wear testing has been conducted on pin-on-disk equipment, beginning with Robin's machine in 1910 (30). This machine wore a pin sample along a single track on the surface of an abrasive cloth fixed to the flat surface of a disk. Khruschov made a major improvement by making the pin follow a spiral path, like a phonograph, to always encounter fresh abrasive. The work on this type of machine, reviewed by Moore (31), helped establish the effect of many parameters, such as abrasive material and size, specimen load, and speed, on two-body abrasion. Climax Molybdenum Co. developed a pin-on-table machine (32) with several improvements over the pin-on-disk machine. Using a converted milling machine, the moving table with abrasive attached provided a constant surface speed. The test specimen was rotated to abrade the pin surface from all directions. Using the operating parameters from the Climax machine, Mutton (33-34) at Melbourne Research Laboratories developed a pin-on-drum abrasion machine in which a slowly rotating drum was substituted for the moving table. The Bureau's machine is very similar to the Melbourne machine except for a few minor refinements. These latter three machines all can use the same type of abrasive, path length, load, speed of abrasive, and rotational speed of the specimen.

Pin-on-Drum Equipment and Specimen

The equipment consists of a head that rotates the test specimen while traversing the length of a cylindrial surface of a rotating drum covered with abrasive paper (figs. 14-15). The head has three functions. First, it loads the specimen. Second, it translates the specimen slowly along the drum so that only fresh abrasive is encountered. Third, it rotates the test specimen to produce wear scars in all directions across the end of the specimen. The applied load is normally 66.7 N. The 0.5-m-diam drum is covered with abrasive cloth, either Al_2O_3, SiC, or garnet of the desired size, usually 120 to 150 mesh. The abrasive cloth is obtained in rolls, 61 cm wide, from a commercial source. During operation, the pin traverses 12.7 mm parallel to the axis of the drum while the drum makes one revolution. The wear path is 1.6 m per drum revolution. The drum rotates at 1.7 rpm to give a surface speed of 2.7 m/min. The pin specimen rotates at 17 rpm. Through a system of gearing, a

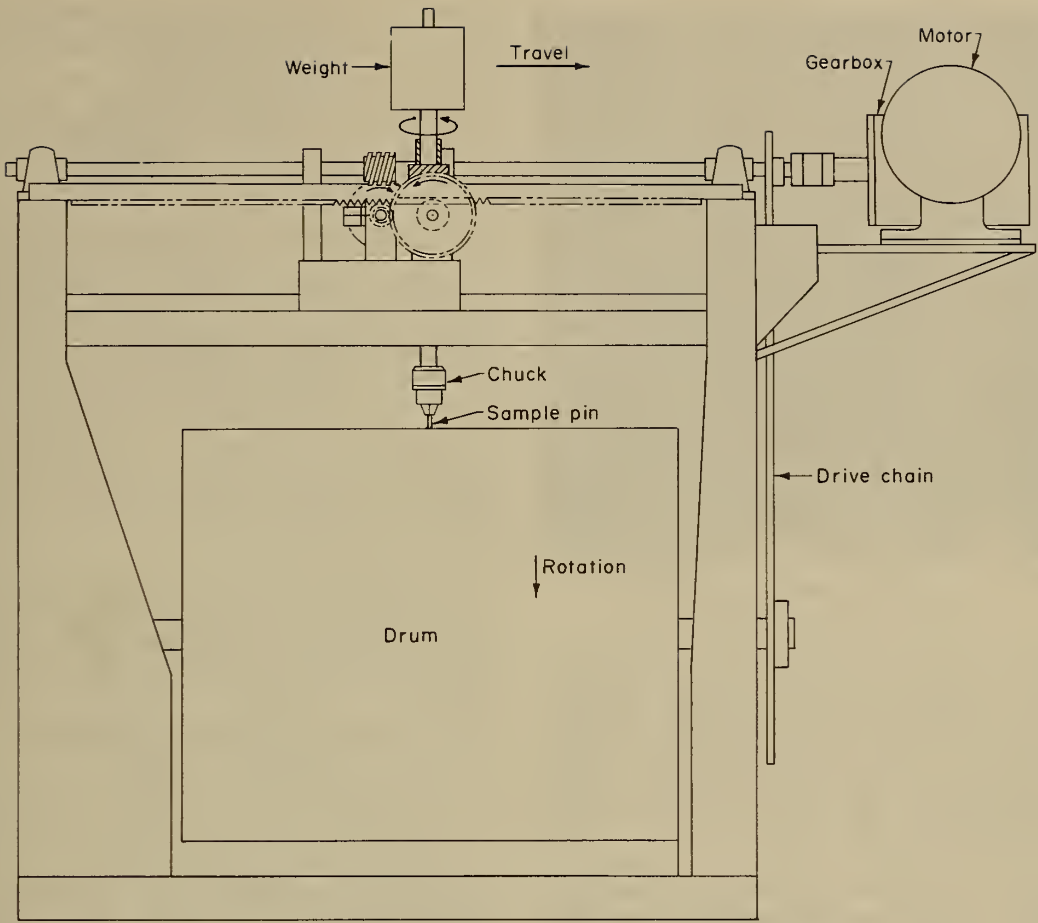

FIGURE 14. - Pin-on-drum abrasive wear test machine, schematic.

single motor drives the entire machine, which automatically stops after completing a preset number of drum revolutions. A gear-disengaging mechanism allows repositioning of the specimen at intervals of 6.35 mm along the drum.

The test specimen consists of a pin 6.35 mm in diam by 2 to 3 cm long. Specimens are normally prepared by machining in a lathe; hard or brittle metal specimens are cut out by electrodischarge machining and then are finish ground in a lathe. Specimens over a wide range of hardness, including soft magnesium and hardened white cast iron, have been evaluated.

Pin-on-Drum Procedure

A new test specimen is worn in for approximately four revolutions, or until its entire end displays wear scars, before beginning the test runs. The test of a material requires two runs—one on the test specimen and one on a standard specimen. The number of drum revolutions is chosen to provide a reasonable amount of wear, that is, about a 40-mg loss. This requires about 6 revolutions (9.6-m path) for soft materials and 12 or more revolutions for hard materials. After the test specimen has been run, the standard specimen is run for the same number of drum revolutions with its track

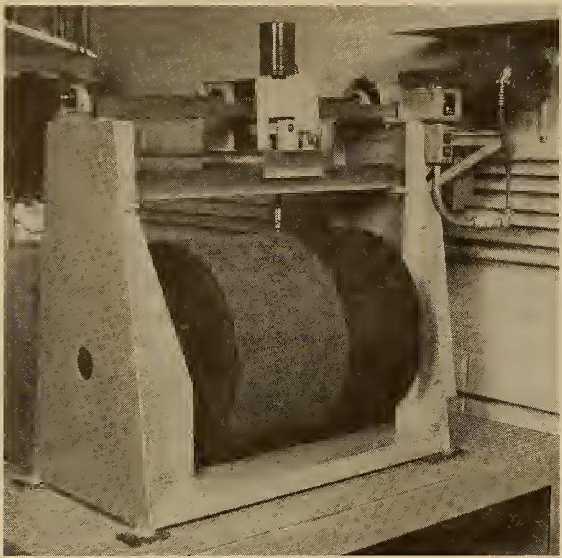

FIGURE 15. - Pin-on-drum abrasive wear test machine.

exactly between the tracks left by the test specimen. The standard material is a low-alloy steel, ASTM A514, with a hardness of HB 269. The standard specimen wear is used to correct for small variations in the abrasiveness of the abrasive cloth from lot to lot and within a given lot.

The corrected mass loss of a test specimen for a given abrasive type under a given load is

$$W = \frac{W_x S}{1.6 S_x},$$

where W is the corrected mass loss of the test specimen per meter of path length,

W_x is the measured mass loss of the test specimen for x number of revolutions,

S_x is the measured mass loss of the standard specimen for the same x number of revolutions,

and S is the long-term average mass loss of the standard specimen per drum revolution.

Specimens are cleaned ultrasonically in water with detergent, rinsed in water, rinsed in alcohol, and air-dried before each weighing.

Test materials of approximately the same density, such as irons and steels, can be compared by weight loss. Materials of differing density should be compared by volume loss. Thus, the wear is reported as cubic millimeters (volume loss) per meter (path length) for a 66.7-N load on the given abrasive.

Pin-on-Drum Results and Discussion

This test apparatus has proven useful in ranking a wide range of materials under the conditions of two-body, high-stress wear. Table 8 shows typical results for a variety of materials, using

TABLE 8. - Typical pin-on-drum wear test data

Alloy[1]	Hardness, HB	Wear loss, mm^3/m	
		120-grit Al_2O_3	150-grit garnet
Pure iron..................	61	1.70	1.86
Mild steel, AISI 1020.......	127	1.67	1.52
Low-alloy steel, AISI 8620..	176	1.28	1.35
Low-alloy steel, ASTM A514..	269	1.225	1.29
Low-alloy steel, AISI 4142..	200	1.035	1.124
Low-alloy steel, AISI 5160..	280	1.009	1.054
High-C steel, AISI 52100....	322	.793	.790
Cr white cast iron..........	410	.446	.267

[1]Steels were in hot-worked condition; cast iron was in as-cast condition.

NOTE.--66.7-N load, 6.4-mm-diam pin.

Al_2O_3 and garnet abrasive cloth. The garnet gives a greater spread in wear values. The results show that wear on pure iron can be reduced to about one-half by alloying to form steel and to about one-fourth by alloying to make white cast iron.

The reproducibility of the test has been very good. In repeating a test immediately, the coefficient of variation has been less than 2 pct. Results on materials retested after several months' time with a different lot of abrasive cloth differed by less than 5 pct from the earlier results.

A set of 12 specimens was used to compare wear on the Bureau's machine with wear on the pin-on-table test of Climax Molybdenum Co. The results gave very nearly the same ranking of materials, but the wear on the Climax machine was consistently about 11 pct less for the same load, path length, and abrasive type.

High-Speed Impact-Gouging Test

A new and promising method for transporting raw materials from a mine is by pneumatic pipeline. This method uses a flow of air to transport solid particles of rock or ore through a pipeline. Lifting ore from underground to the surface pneumatically has great economic potential but is limited by severe wear problems. Pneumatic conveying is currently used for backfilling underground mines and trenches, removing tunnel muck, and transporting coal and ores within an underground mine.

During pneumatic transport, severe wear at pipe bends is caused by collision of solid particles with the interior of the pipe. The particles may be as large as 6 to 10 cm across, traveling at speeds up to 40 m/s. Elbows have been known to wear through after only a few hours of use. A limited amount of research has been done to evaluate the erosive wear of bends used in pneumatic transport. Mills and Mason (35-38) used a closed-loop experimental apparatus to simultaneously determine the wear rates of six pipe bends. Kostka (39) used coarse solid particles in a commercial-sized pneumatic transport system to study erosive wear in different types of pipe bends.

No prior experimental apparatus has been developed to study the effect of high-impact abrasive wear caused by large particles with a mass greater than a few grams. The Bureau has designed and constructed test equipment capable of shooting a 1-kg projectile at a test specimen at speeds up to 45 m/s. The test has been named the high-speed impact-gouging test. The wear condition is classified as high-stress, two-body abrasive wear. The condition is considered high-stress because the abrasive projectile suffers appreciable damage during impact.

High-Speed Impact Equipment and Specimen

The test equipment consists of an air gun that shoots rock projectiles at a stationary specimen located a short distance from the muzzle. The specimen stage can be tilted to vary the angle between the projectile line of flight and the specimen surface. The test equipment is shown in figures 16 and 17. The projectile is a cylinder 7 cm in diam by 10 cm long, weighing 1 kg. Solid granite cores can be used, but for economy, a concrete cylinder with a granite disk about 2 cm thick on the impact end is used. A pin through the side of the tube holds the projectile in place while driving gas is admitted to give the desired pressure. A chronograph is used to determine the velocity of the projectile after it exits the tube. A box below the impact area collects debris from the shattered projectiles, and a safety shield covers the end of the tube and the impact area.

The test specimens are normally 7.6 by 2.5 by 1.3 cm, with beveled ends for clamping. They are interchangeable with the jaw crusher test specimens previously described.

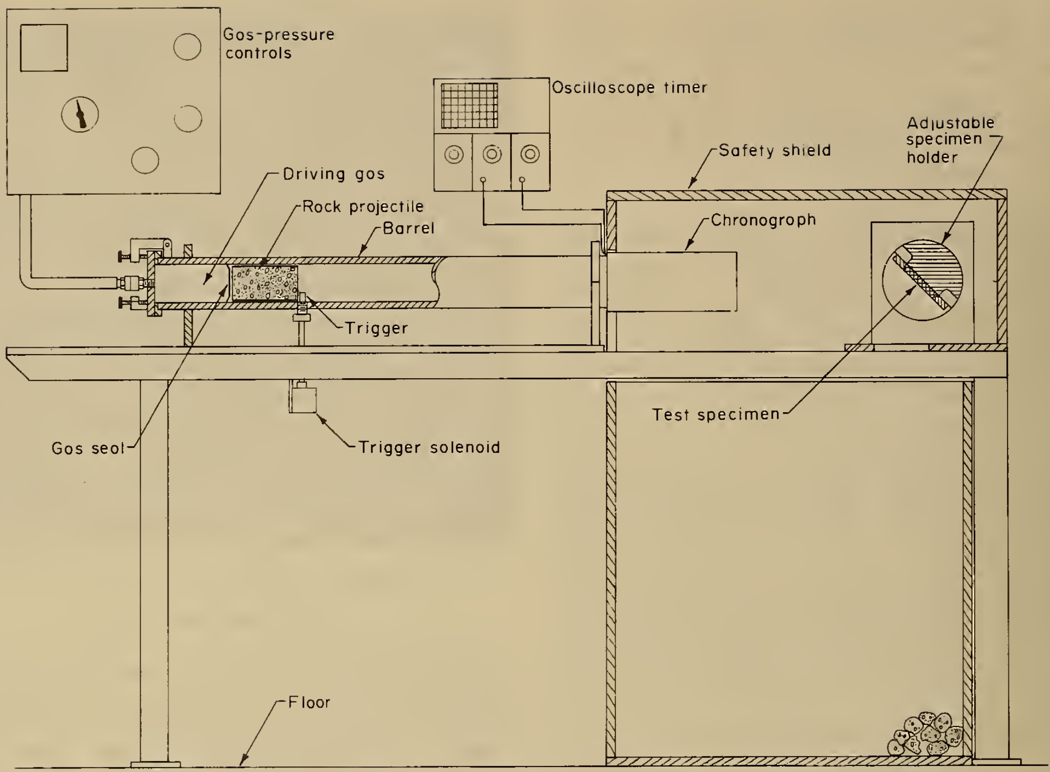

FIGURE 16. - High-speed impact-gouging test machine, schematic.

High-Speed Impact Procedure

The specimens are cleaned, dried, and mounted on the target face, with the angle of incidence set by adjusting and locking the target. The tube is cleaned and sprayed with a Teflon fluorocarbon polymer coating that lowers friction and wear. The projectile is loaded into the tube, a rubber seal is placed behind the projectile, and the breech is closed. Gas is admitted to the chamber to a specified pressure, the chronograph is set, and the projectile is released by actuating the solenoid that retracts the retaining pin.

After the projectile is shot, the time recorded by the oscilloscope is noted and used to calculate the projectile velocity. The target specimen is removed, cleaned with a brush, and soaked in concentrated hydrofluoric acid in order to remove the embedded silicate material. The specimen is then dried and weighed. The barrel is cleaned for the next run.

Although the test equipment is relatively new, several general findings can be reported. Examination of the specimen surfaces of mild steel after impact has revealed gouges resulting from ductile deformation. The gouge scars are much deeper but shorter at a 45° angle of impact than at a 15° angle. The harder steel alloy specimens have exhibited much smaller wear scars and indicate some degree of brittle fracture. It is possible that brittleness is induced by the high strain rate produced by this test.

IMPACT-SPALLING WEAR

Many types of ore crushing and grinding equipment, such as hammer mills, rod mills, and ball mills, subject wear parts to repetitive impacts. The wear that results from fatigue, spalling, chipping,

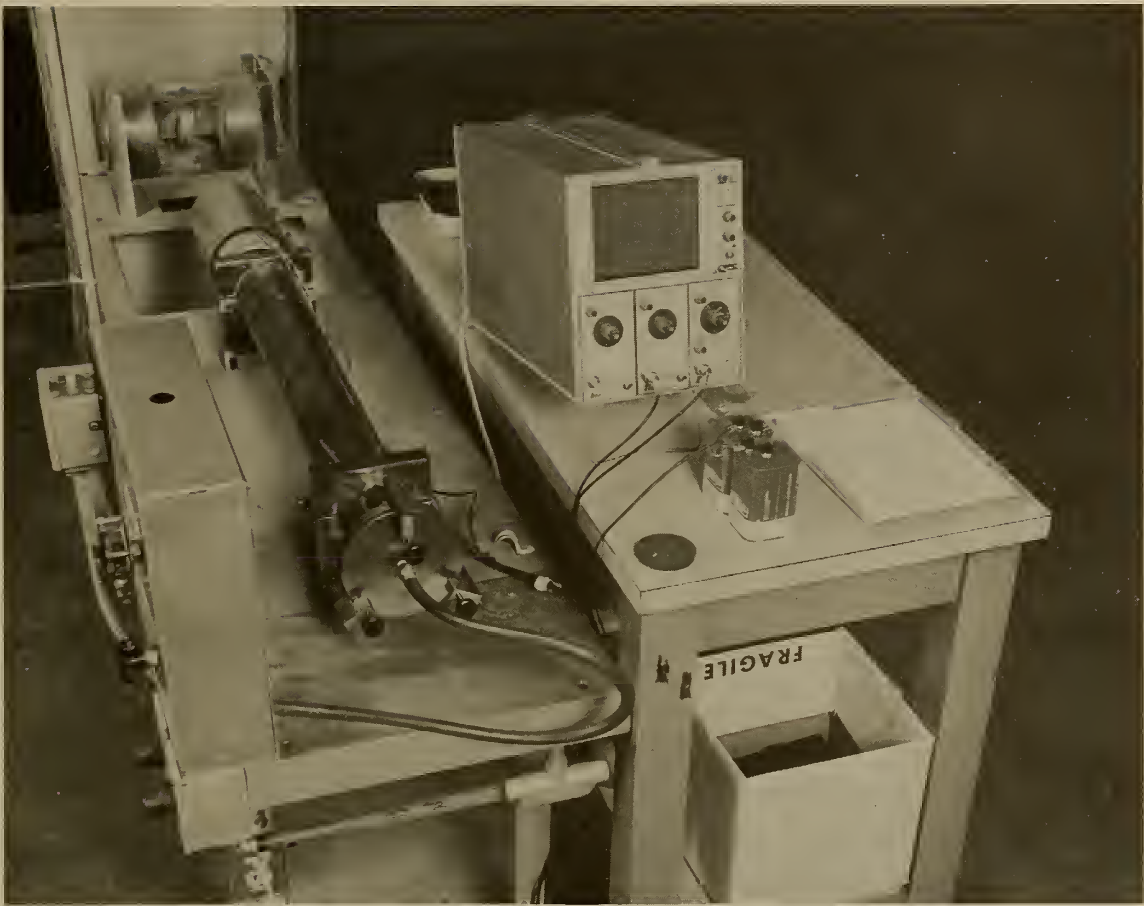

FIGURE 17. - High-speed impact-gouging test machine.

and fracturing can be more severe than abrasive wear. This is especially true of very hard alloys such as martensitic steels and alloyed white cast irons with their superior abrasion resistance but with a propensity to spall or break after large numbers of impacts (40). Neither fracture toughness nor Charpy impact tests have proven useful for predicting behavior of the relatively brittle, wear-resistant materials subjected to repeated impacts (41).

Ball-on-Block Impact-Spalling Test

A test that simulates the type of wear caused by repetitive impacts is the ball-on-block impact-spalling test. The testing machine drops steel balls repeatedly onto a test block, as described fully by Blickensderfer and Forkner (42). The impacts are concentrated onto one relatively small area on the test block. Testing machines of similar concept were used previously by Dixon (43) and Durman (44). Machines of this type have been useful for obtaining laboratory data on the spalling and fracture resistance of materials subjected to repeated impacts.

Ball-on-Block Equipment and Specimen

The machine consists of a steel frame, a conveyor for lifting balls, ramps for transporting balls, and an anvil for supporting a specimen inside a large funnel that collects the rebounding balls, as shown in figures 18 and 19. The

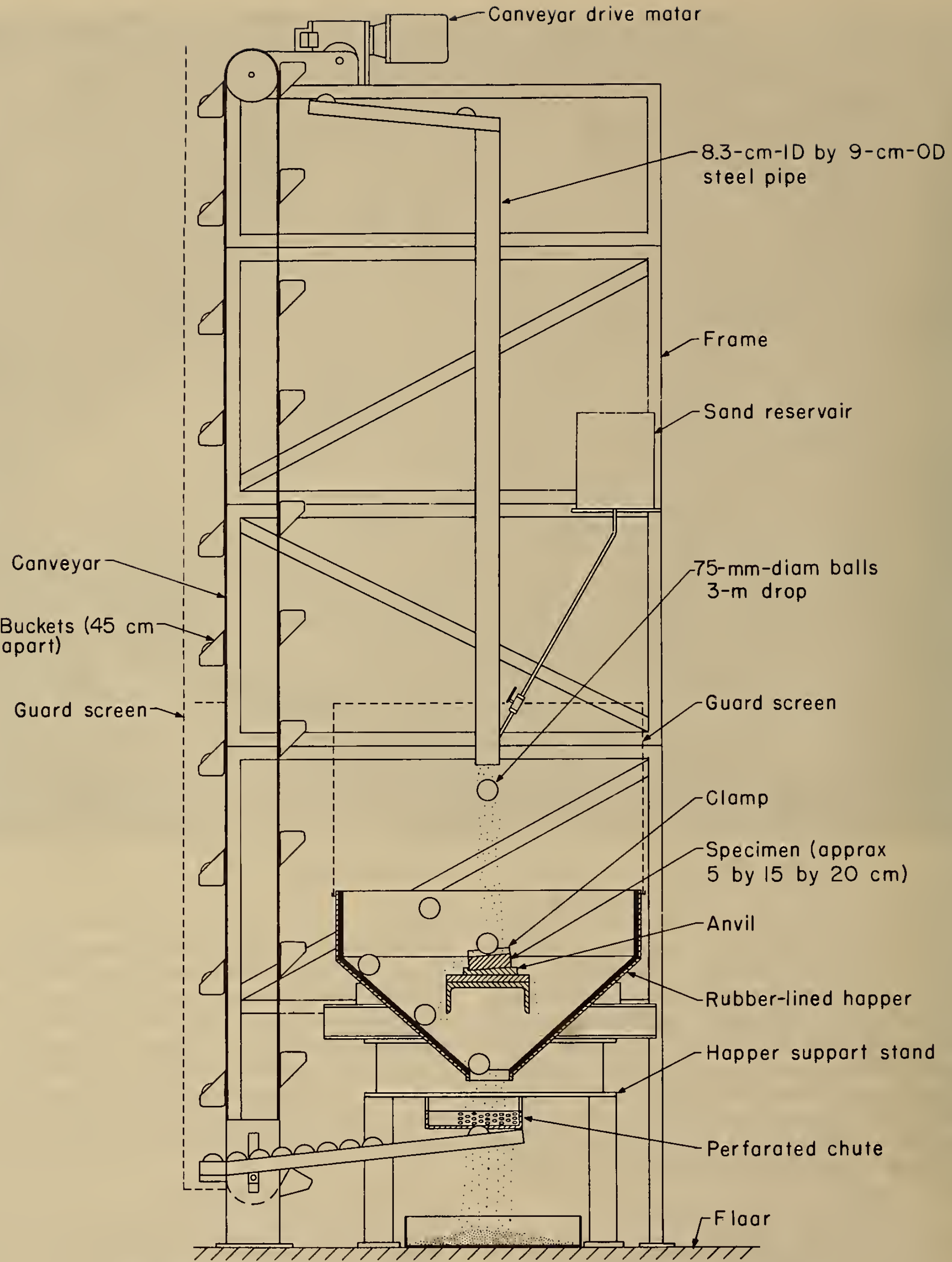

FIGURE 18. - Ball-on-block impact-spalling test machine, schematic.

FIGURE 19. - Ball-on-block impact-spalling test machine.

commercial steel balls used are 75 mm in diam and weigh about 1.8 kg. From the top of the conveyor, the balls roll into a vertical tube that directs them onto the test block after a fall of 3 m. Silica sand is continuously fed onto the test block in order to more closely simulate the condition in a ball mill wherein ore is present on the liners. The number of impacts is displayed by a counter that is actuated when a ball interrupts a light beam across the lower ramp.

Test blocks are approximately 50 mm thick, 15 cm wide, and 20 cm long. The 15- by 20-cm face is the impact surface. Blocks are surface-ground on the bottom to ensure good contact with the anvil. If the quality of a cast block is questionable, it should be X-rayed first, in order that valuable test time is not spent on inferior materials.

Ball-on-Block Procedure

The test block is clamped securely to the anvil, and safety guards are installed. The balls, normally 12, are placed in the machine. The sand flow and conveyors are turned on. With the conveyor running at a speed of 38 m/min, about 2,000 impacts per hour are delivered to the test block. A block is tested until it breaks or 100,000 impacts are delivered. During the test, the weight loss and size of the developing crater are measured at intervals of 10,000, 20,000, 35,000, 60,000, and 100,000 impacts. During operation, an area within 2 m of the machine is blocked off to prevent injury to personnel because occasionally a ball escapes from the machine with sufficient energy to cause severe injury.

Ball-on-Block Results and Discussion

Four types of failures have been observed, namely, cold flow, flaking, spalling, and breakage. The softer and more ductile steel alloys tend to cold flow and flake. Cold flow describes the movement of bulk metal by plastic deformation and is identified by an impact crater and rounded edges of the block. Flaking describes the formation and subsequent separation from the surface of thin flakes of metal that develop from fatigue. Cold flow and flaking occur together but to differing degrees depending upon the particular alloy.

Spalling and breakage tend to occur on the harder (more wear-resistant) alloys. Spalling describes the separation of pieces of material of about 3- to 6-mm dimensions. A crater develops in the impact region as a consequence of spalling. If a block fractures into two or more major pieces, it is termed breakage. Blocks may or may not spall before breakage occurs, depending upon the composition and heat treatment.

Data showing typical test results are given in table 9.

TABLE 9. - Typical ball-on-block impact-spalling data

	High-Cr-Mo white cast iron	Mild steel, AISI 1020	Martensitic Cr-Mo steel	Ni white cast iron
Hardness..........HB..	670	156	550	580
Number of impacts.....	100,000	100,000	100,000	14,000
Type of failure.......	Spalling	(1)	Flaking	Breakage
Wt loss....mg/impact..	5.1	0.82	0.09	Neg.
Crater size:				
Diameter........cm..	10.7	12.7	5.8	Neg.
Depth...........cm..	1.1	0.25	0.28	Neg.
Volume.........cm^3..	21.7	6.3	1.1	Neg.

Neg. Negligible. [1]Cold flow, flaking.

NOTE.--1.8-kg steel balls, 3-m drop height, 5-cm-thick test block.

Ball-on-Ball Impact-Spalling Test

The ball-on-ball impact-spalling test is designed to create large numbers of impacts on test materials in a relatively short time. Designed and constructed by the Bureau, the test is an advance over the earlier ball-on-block drop tests because of at least a twenty-fold increase in testing speed. The test, described in greater detail by Blickensderfer and Tylczak (45), has proven especially useful for studying the spalling of alloyed white cast irons and for comparing the resistance to breakage of commercial and experimental grinding balls. Because the impacts are distributed randomly over the entire surface of the ball specimen, the entire surface becomes highly stressed under compression.

Ball-on-Ball Equipment and Specimens

Balls are impacted against each other in a manner that provides many impacts in a relatively short time. A ball is dropped 3.5 m onto a column of balls contained in a curved tube, as shown in figure 20. The impact from the dropped ball is transmitted through the column of balls with each successive ball receiving a ball-on-ball impact on each side. The kinetic energy of the first impact is 54 J. The energy of subsequent impacts through the tube decreases until it is about 5 J at the last impact. The energy in the last ball carries it out of the end of the tube onto a ramp where the ball actuates a counter and rolls into a bucket conveyor that carries it to the top of the machine to be dropped again. The machine provides random occasional mixing of the balls as described in reference 45, to give different neighbors to each ball over a period of time.

Two advantages of the design are (1) it produces many impacts quickly on a group of balls, and (2) the impacts are of variable intensity, as found in a real ball mill.

The test balls are 75 mm in diam and weigh about 1.8 kg. Both cast and forged steel balls and cast iron balls have been

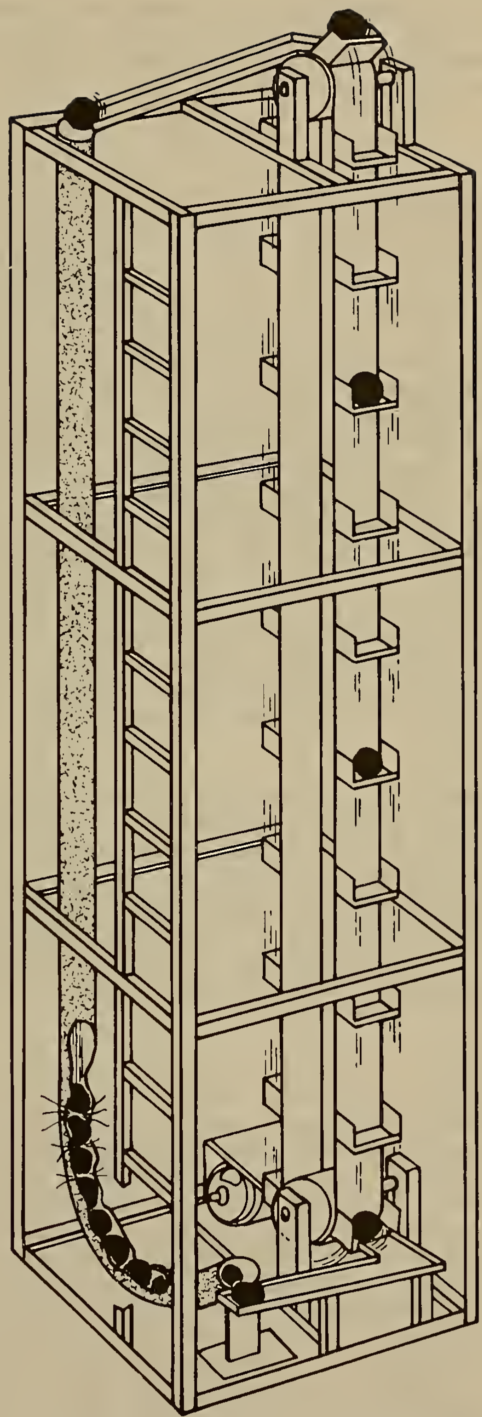

FIGURE 20. - Ball-on-ball impact-spalling test machine, schematic.

used. Because many different ball specimens are run simultaneously, they are identified by grinding small flats on their surfaces.

Ball-on-Ball Procedure

To start a test, 22 balls are loaded into the machine. During operation there are typically 18 balls in the tube and 4 in the ramps and in the conveyor buckets. The machine drops about 22 balls per minute. For each ball dropped, 36 impacts are created--two on each ball in the tube except the one dropped and the one leaving the tube. This gives a rate of about 45,000 total impacts per hour in the system. The machine is run unattended. When a ball breaks, the pieces block the tube or ramp and all balls cease to circulate. Although the conveyor continues running, the ball drop count remains fixed on the counter. An area within 2 m of the machine is blocked off during operation to prevent injury to personnel because if a ball escaped from the machine, it could cause severe injury to a person.

Balls are tested until they break or until they spall excessively. Experience showed that balls that have spalled over 150 g do not roll down the ramps; therefore, a ball is removed from the test after it has lost 100 g by spalling. All balls are removed from the tube and weighed at intervals of 5,000 to 20,000 impacts per ball. Accurate accounting of the impacts is kept on each ball. A ball that fails is replaced with either another test ball or a hardened steel filler ball, and the test is continued.

Ball-on-Ball Results and Discussion

Four types of failures have been observed: (1) spalling, pieces of 2 to 5 cm across and up to 1 cm thick, (2) minispalling, small deep crescent pits 2 to 4 mm across and 2 to 3 mm deep, (3) flaking, very thin flakes with extreme surface cold work, and (4) breakage, a complete failure of the ball, often by fracturing through the center of the ball.

The type of failure of a ball seems to be dependent on hardness and the means by which the balls were produced. Spalling occurs mainly in cast balls and starts within 50,000 impacts. Minispalling occurs in forged, hard (about HRC 62 to 64) steel balls and does not start until 100,000 or more impacts. Flaking and plastic deformation are the only damage that occur to the softer (less than HRC 40) forged steel balls. The flakes develop after 60,000 or more impacts. Breakage occurs in fully hard (greater than HRC 63) steel balls and unheat-treated cast balls and can occur any time from a few to a few hundred thousand impacts. Additional results are presented by Blickensderfer (45-46).

SUMMARY

The research laboratories of the Bureau of Mines have the capability to conduct a large variety of wear tests relevant to the mining and minerals processing industries. The tests include several pertinent ASTM standard tests and proposed standard tests. The abrasive wear tests include one low-stress, three-body wear test (dry-sand, rubber-wheel abrasive wear test); five low-stress, two-body wear tests; two high-stress, three-body wear tests (jaw crusher and ball mill); and two high-stress, two-body wear tests (pin-on-drum and high-speed impact-gouging).

The repetitive impact tests include a ball-on-block impact-spalling test and a novel ball-on-ball impact spalling test. The latter is capable of producing impacts at a much faster rate than previous tests of this type.

Comparisons of the tests, test conditions, and other parameters are summarized in tables 10 and 11.

TABLE 10. - Summary of Bureau of Mines wear tests

Name of wear test	Type of wear	Wear condition	Simulated field conditions
Dry-sand, rubber-wheel	Abrasive	Low stress, 3-body	Chutes, bins, conveyors. Pivot pins, linkages operating in minerals. Dirty wire rope.
Taber Abraser	...do	Low stress, 2-body	Removal of material by grinding wheels.
Abrasion resistance of refractory materials.	...do	...do	Hard-particle-handling refractory liners.
Dry-particle erosive	...do	...do	Dust-handling equipment: blowers, baghouse components, flues.
Elevated-temperature, dry-particle erosive.	...do	...do	Dust-handling equipment: blowers, baghouse components, flues, at elevated temperatures.
Low-angle slurry pot	...do	...do	Slurry-handling equipment: pumps, pipelines, fittings, sluices, spirals.
Jaw crusher gouging	...do	High stress, 3-body	Ore comminution equipment: jaw and gyratory crushers, ball and rod mills.
Ball mill, 12-cm diam and 60-cm diam.	...do	...do	Ball mills.
Pin-on-drum	...do	High stress, 2-body	Rock penetrators: excavator teeth, drill bits, coal bits, bucket lips.
High-speed impact-gouging	...do	...do	Centrifugal ore breaker, pneumatic transport of rock and ore.
Ball-on-block	Impact-spalling	Concentrated repeated impact	Ball and rod mill liners, other repeated impact conditions.
Ball-on-ball	...do	Distributed repeated impact.	Ball mills, rod mills, hammer mills, other repeated impact conditions.

TABLE 11. - Summary of wear test parameters

Name of wear test	ASTM standing, Jan. 1984	Specimen size, mm	Number of specimens	Duration	Speed, m/s	Abrasion distance, m	Wear per specimen, mm^3
Dry-sand, rubber-wheel	G65-81	12 by 25 by 75	1	30 s to 30 min	2.4	72 -4,309	10 - 150
Taber Abraser	None	100 by 100 or 160 diam.	1- 2	8 s to 14 min	.3	2.7- 270	2 - 10
Abrasion resistance of refractory materials	C704-76a	30 by 30 by 30	1	10 min	Unknown	NAp	1,000 - 5,000
Dry-particle erosive	In committee	2 by 15 by 15	1	5 min or more	30-120	NAp	.2- 1
Elevated-temperature, dry-particle erosive	None	2 by 13 by 13	1-12	5 min or more	30-170	NAp	.2- 1
Low-angle slurry pot	...do	10 by 24 by 32	8	30 min to 12 h	3- 22	NAp	.2- 75
Jaw crusher gouging	In committee	12 by 25 by 75	[1]2	1 h	.02	NAp	30 - 2,000
Ball mill, 12-cm diam	None	20 diam	5-20	1-10 h	1.4	NAp	.1- 10
Ball mill, 60-cm diam	...do	50 diam	6-30	1-10 h	3.1	NAp	10 - 100
Pin-on-drum	...do	6.4 diam by 25	1	7-20 min[2]	.045	9.6- 25.6	2 - 25
High-speed impact-gouging	...do	12 by 25 by 75	1	10^{-3} s	20- 50	.01	2 - 10
Ball-on-block	...do	50 by 150 by 200	1	50 h	7.7	NAp	1,000 -50,000
Ball-on-ball	...do	75 diam sphere	22-24	100 h	7.7	NAp	12,000 -20,000

NAp Not applicable. [1]Requires 2 identical test specimens and 2 standard specimens.
[2]Includes time required to run standard pin.

REFERENCES

1. American Society for Testing and Materials. Evaluation of Wear Testing (Symp., 71st Annu. Meeting ASTM, San Francisco, CA, June 23-28, 1968). ASTM, Philadelphia, PA, Spec. Tech. Publ. 446, 1969, 132 pp.

2. Bayer, R. G. (ed.). Selection and Use of Wear Tests for Metals (Symp., Nov. Committee Week, ASTM, New Orleans, LA, Nov. 17-21, 1975). ASTM, Philadelphia, PA, Spec. Tech. Publ. 615, 1975, 111 pp.

3. Borik, F. Using Tests To Define the Influence of Metallurgical Variables on Abrasion. Met. Eng. Q., v. 12, No. 2, 1972, pp. 33-39.

4. Tweeton, D. R. Effect of Environment on Friction and Wear Between Quartz and Steel. BuMines RI 8124, 1976, 25 pp.

5. American Society for Testing and Materials. Standard Practice for Conducting Dry Sand/Rubber Wheel Abrasion Tests. G65-81 in 1981 Annual Book of ASTM Standards: Part 10, Metals--Physical, Mechanical, Corrosion Testing. Philadelphia, PA, 1981, pp. 1044-1061.

6. ______. Standard Method of Test for Abrasion Resistance of Refractory Materials at Room Temperature. C704-76a in 1981 Annual Book of ASTM Standards: Part 17, Refractories, Glass, and Other Ceramic Materials; Manufactured Carbon and Graphite Products. Philadelphia, PA, 1981, pp. 710-714.

7. Bhat, M. S., V. F. Zackay, E. R. Parker, and I. Finnie. Wear Resistant Alloys for Coal Handling Equipment. Prog. Rep. for the period Oct. 1, 1977-Sept. 30, 1979, Rep. ZP8006. Univ. CA, Berkeley, CA, 1979, 63 pp.

8. Borik, F. Rubber Wheel Abrasion Test. Pres. at SAE Combined National Farm, Construction & Industrial Machinery and Powerplant Meetings, Milwaukee, WI, Sept 14-17, 1970. SAE preprint 700 687, 1970, pp. 1-12.

9. Levy, A. V. The Solid Particle Erosion Behavior of Steel as a Function of Microstructure. Wear, v. 68, No. 3, 1981, pp. 269-287.

10. Head, W. J., and M. E. Harr. The Development of a Model To Predict the Erosion by Natural Contaminants. Wear, v. 15, No. 1, 1970, pp. 1-46.

11. Finnie, I., Y. Kabil, and J. Wolok. Erosion of Metals by Solid Particles. J. Mater., v. 2, No. 3, 1967, pp. 682-700.

12. Ruff, A. W., and L. K. Ives. Measurement of Solid Particle Velocity in Erosive Wear. Wear, v. 35, No. 1, 1975, pp. 195-199.

13. Finnie, I. Erosion of Surfaces by Solid Particles. Wear, v. 3, No. 2, 1960, pp. 87-103.

14. Doyle, P. A., and A. V. Levy. The Elevated Temperature Erosion of 1100 Al by Gas Particle Flow. Paper in Proceedings of TMS of AIME (Conf. on Corrosion/Erosion Behavior of Mater., St. Louis, MO, Oct. 17-19, 1978). Metall. Soc. AIME, Warrendale, PA, pp. 162-176.

15. Young, J. P., and A. W. Ruff. Particle Erosion Measurements on Metals. J. Eng. Mater. and Technol., v. 99, No. 2, 1977, pp. 121-125.

16. Hansen, J. S., J. E. Kelley, and F. W. Wood. Erosion Testing of Potential Valve Materials for Coal Gasification Systems. BuMines RI 8335, 1979, 26 pp.

17. Jackson, L. D. A. Controlling Abrasion in Slo Slurry Pipeline Systems. Can. Min. J., v. 95, No. 11, 1974, p. 42.

18. Tsai, W., J. A. C. Humphrey, I. Cornet, and A. V. Levy. Experimental Measurement of Accelerated Erosion in a Slurry Pot Tester. Wear, v. 68, No. 3, 1981, pp. 289-303.

19. Bess, M. L. Erosion-Corrosion of Cast Pump Alloys. Pres. at Pac. Northwest Met. and Miner. Conf., Seattle, WA, May 6, 1977, 24 pp.; available from B. W. Madsen, Albany Research Center, BuMines, Albany, OR.

20. Postlethwaite, J., B. J. Brady, M. W. Hawrylak, and E. B. Tinker. Effects of Corrosion on the Wear Patterns in Horizontal Slurry Pipelines. Corrosion (Houston), v. 34, No. 7, 1978, pp. 245-250.

21. Hocke, H., and H. N. Wilkinson. Testing Abrasion Resistance of Slurry Pipeline Materials. Tribol. Int., v. 5, Oct. 1978, pp. 289-294.

22. Elkholy, A. Prediction of Abrasion Wear for Slurry Pump Materials. Wear, v. 84, No. 1, 1983, pp. 39-49.

23. Borik, F., and D. L. Sponseller. Gouging Abrasion Test for Materials Used in Ore and Rock Crushing: Part I - Description of the Test. J. Mater., v. 6, No. 3, 1971, pp. 576-589.

24. Borik, F., and W. G. Scholz. Gouging Abrasion Test for Materials Used in Ore and Rock Crushing: Part II - Effect of Metallurgical Variables on Gouging Wear. J. Mater., v. 6, No. 3, 1971, pp. 590-605.

25. Sare, I. R., and W. B. Hall. The Determination of Gouging Abrasion Resistance by Jaw Crusher Tests. Paper in Conference on Lubrication, Friction, and Wear in Engineering, Melbourne, Australia, Dec. 1-5, 1980. Inst. Eng., Barton, A.C.T., Australia, 1982, pp. 94-98; order No. ISBN 085825-148-5.

26. Natarajan, K. A., S. C. Riemer, and I. Iwasaki. Ball Wear in Magnetic Taconite Grinding. Pres. at 56th Annu. Meet. MN Sec. AIME and 44th Annu. Min. Symp., Univ. MN, Duluth, MN, Jan. 12-13, 1983, 9 pp.; available from I. Iwasaki, Univ. MN, Minneapolis, MN.

27. Bond, F. C. Lab Equipment and Tests Help Predict Metal Consumption in Crushing and Grinding Units. Eng. and Min. J., v. 165, No. 6, 1964, pp. 169-175.

28. Ellis, O. W. Wear Tests on Ferrous Alloys. Trans. Am. Soc. Met., v. 30, 1942, pp. 249-286.

29. Norman, T. E., and E. M. Loeb. Wear Tests on Grinding Balls. Trans. AIME, v. 176, 1948, pp. 490-526.

30. Robin, F. Usure des Aciers aux Abrasifs (The Wear of Steels by Abrasives). Rev. Metall. (Paris), v. 8, 1911, pp. 47-84.

31. Moore, M. A. A Review of Two-Body Abrasive Wear. Wear, v. 27, No. 1, 1974, pp. 1-17.

32. Muscara, J., and M. J. Sinnott. Construction and Evaluation of a Versatile Abrasive Wear Testing Apparatus. Met. Eng. Q., v. 12, No. 2, 1972, pp. 21-32.

33. Mutton, P. J. High Stress Abrasion Testing of Wear Resistant Steels and Cast Irons. Broken Hill Proprietary Co., Melbourne Res. Lab., Clayton, Victoria, Australia, Lab. Rep. MRL/PM3/78/001, Aug. 1978, 49 pp.

34. _____. High Stress Abrasion Testing of Wear Resistant Materials. Broken Hill Proprietary Co., Melbourne Res. Lab., Clayton, Victoria, Australia, Tech. Bull., v. 24, No. 1, 1980, pp. 38-44.

35. Mills, D., and J. S. Mason. Evaluating the Conveying Capacity and Service Life of Pipe Bends in Pneumatic Conveying Systems. J. Powder & Bulk Solids Technol., v. 3, No. 2, 1979, pp. 13-20.

36. _____. Particle Size Effects in Bend Erosion. Wear, v. 44, No. 2, 1977, pp. 311-328.

37. Mills, D., and J. S. Mason. The Effect of Particle Size on the Erosion of Pipe Bends in Pneumatic Conveying Systems. Paper 4 in Proceedings of the Sixth (Int.) Conference on Powder Technology (Birmingham, United Kingdom, Mar. 6-9, 1979, session H). Spec. Exhibition Ltd., Croydon, Surry, England, 1979, pp. H50-H96.

38. _____. The Influence of Velocity on the Erosive Wear of Pipe Bends in Pneumatic Conveying Systems. Paper in Proceedings of the Technical Program: International Powder and Bulk Solids Handling and Processing (Philadelphia, PA, May 15-17, 1979). Ind. and Sci. Conf. Manage., Inc., Chicago, IL, 1979, pp. 300-314.

39. Kostka, K. S. Coarse Particle Erosion in Pneumatic Conveyor Bends. Pneumotransport 4. Paper F8 in Fourth Conference (International) on Pneumatic Transport of Solids in Pipes (Carmel-by-the-Sea, CA, June 26-28, 1978). Mater. Handling Div., ASME, 1978, pp. F8-87 to F8-102.

40. Dodd, J. Progress in the Development and Use of Abrasion Resistant Alloy Irons and Steels in the Mining Industry. Trans.-Soc. Min. Eng. AIME, v. 270, 1981, pp. 1923-1930.

41. Diesburg, D. E. Fracture Toughness Test Methods for Abrasion-Resistant White Cast Irons Using Compact Specimens. Paper in Fracture Toughness and Slow-Stable Cracking (Proc. 1973 Natl. Symp. on Fracture Mechanics). ASTM, Philadelphia, PA, Spec. Tech. Publ. 559, 1973, pt. 1, pp. 3-14.

42. Blickensderfer, R., and B. F. Forkner. A Ball-on-Block Impact-Spalling Wear Test and Results on Several Iron Alloys. BuMines RI 8794, 1983, 18 pp.

43. Dixon, R. H. T. Some Effects of Heat-Treatment Upon the Impact-Fatigue Life of Ni-Hard Grinding Balls. J. Iron and Steel Inst., London, Jan. 1961, pp. 40-48.

44. Durman, R. W. Basic Metallurgical Concept and the Mechanical Testing of Some Abrasion-Resistant Alloys. Foundry Trade J., v. 134, May 1973, pp. 645-651.

45. Blickensderfer, R., and J. H. Tylczak. A Large-Scale Impact Spalling Test. Wear, v. 84, No. 3, 1983, pp. 361-373.

46. Blickensderfer, R., J. H. Tylczak, and J. Dodd. The Effect of Heat Treatment on Spalling of a Cr-Mo White Cast Iron. Paper in Wear of Materials 1983. ASME, New York, 1983, pp. 471-476.

☆U.S. GPO: 1985-505-019/5091

INT.-BU.OF MINES,PGH.,PA. 27832

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
4800 FORBES AVENUE
PITTSBURGH, PENNSYLVANIA 15213

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

AN EQUAL OPPORTUNITY EMPLOYER

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF THE INTERIOR
INT-416

- [ ] Return to sender.
- [ ] Do not wish to receive this material, please remove from your mailing list.
- [ ] Address change. Please correct as indicated.